Neutrino Mass Ordering
and the Neutrino-nian Knot

* There's not a lot of Alexander the Great clipart.
Hercules will be his stand-in.

δ_{CP}

$\text{sign}(\Delta m_{32})$

θ_{23}

Keith Matera

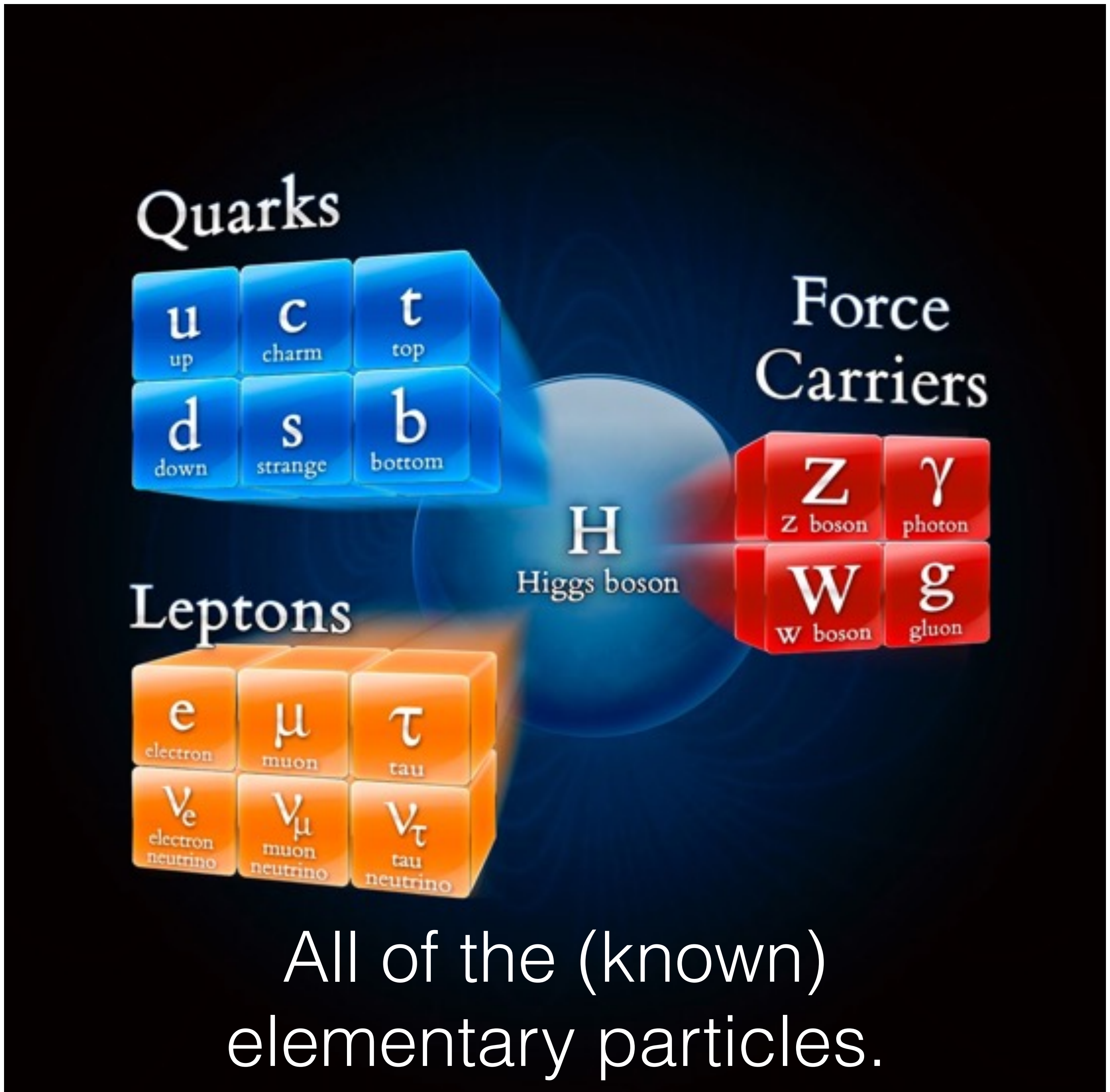
FNAL Undergraduate Lecture Series —July 26, 2016

PART I

Neutrinos!

The Standard Model

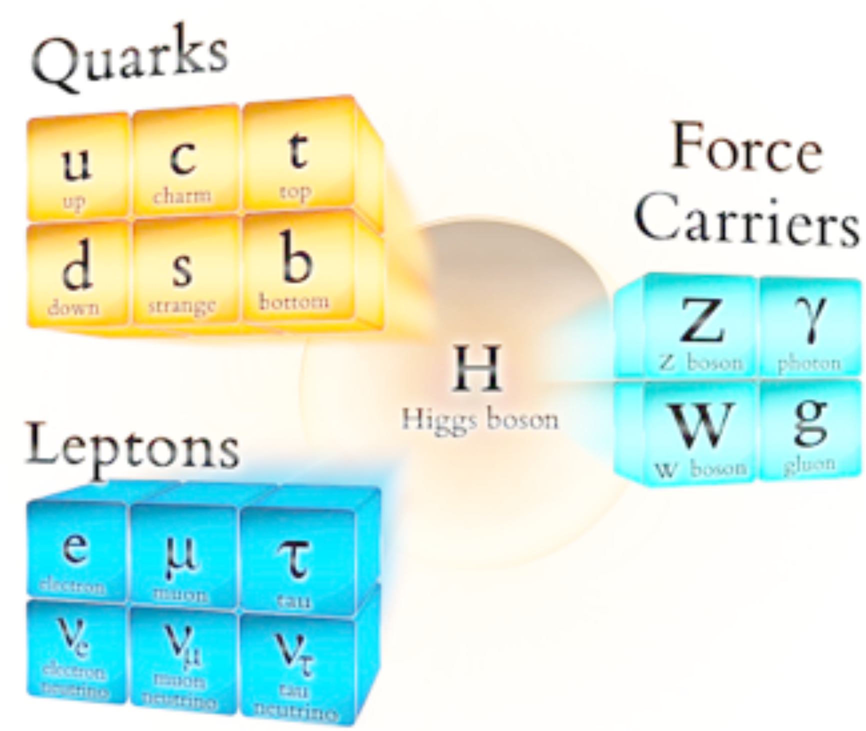
The world map with which we set off on our quest.



All of the (known) elementary particles.

+

Anti-matter

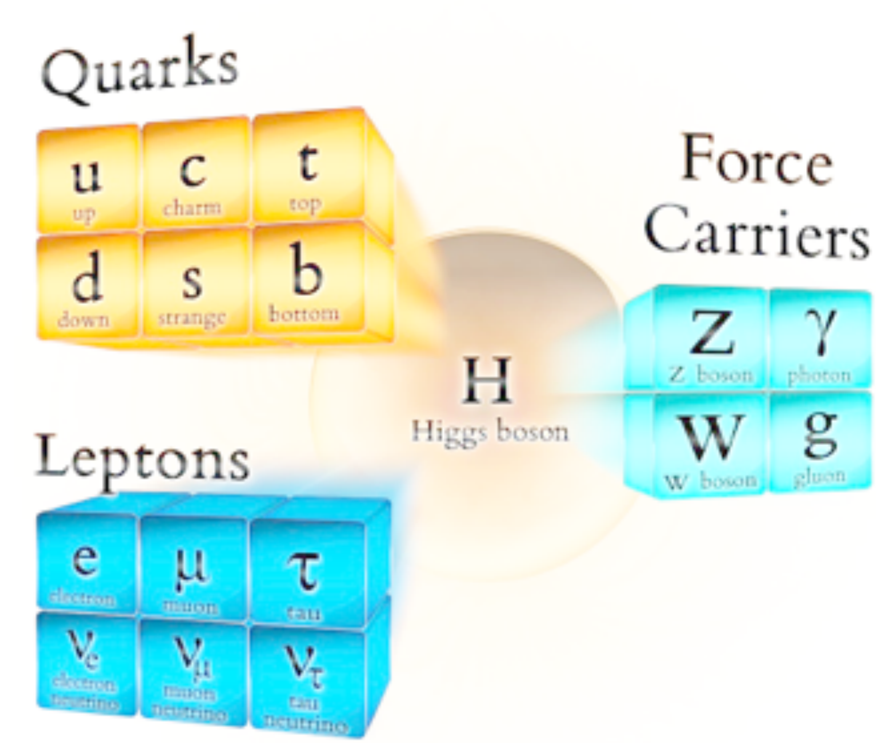


*Disclaimer: Some of these particles (e.g., the photon) are their own anti-particles.

Everyday matter consists of only a small piece of the standard model

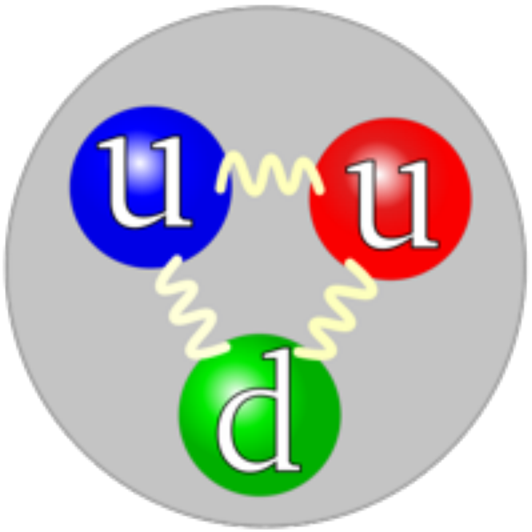
+

Anti-matter

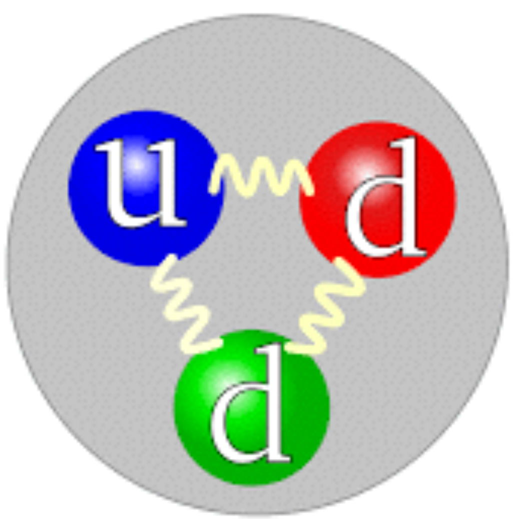


*Disclaimer: Some of these particles (e.g., the photon) are their own anti-particles.

Up and down quarks give us protons and neutrons

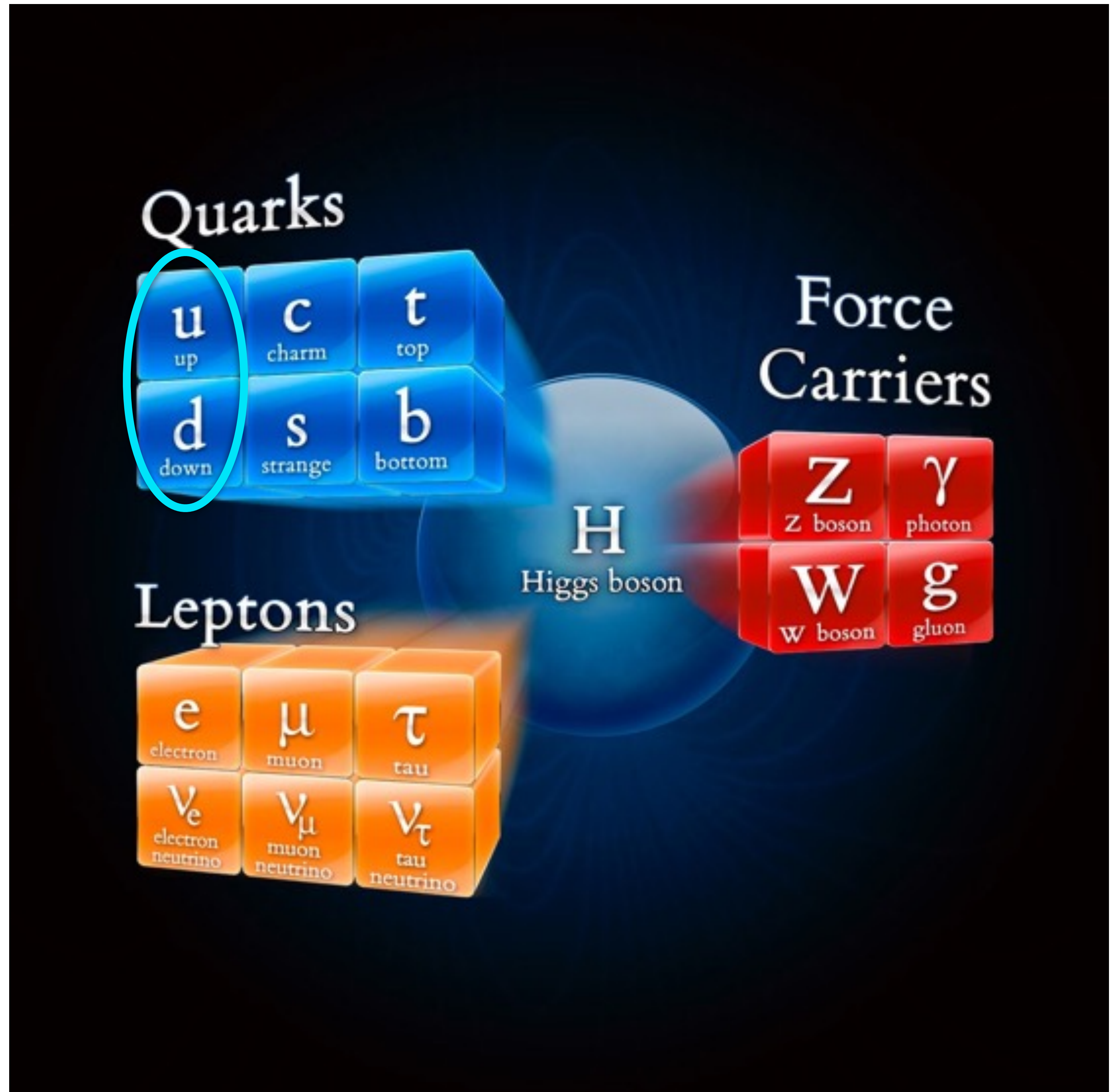


Proton

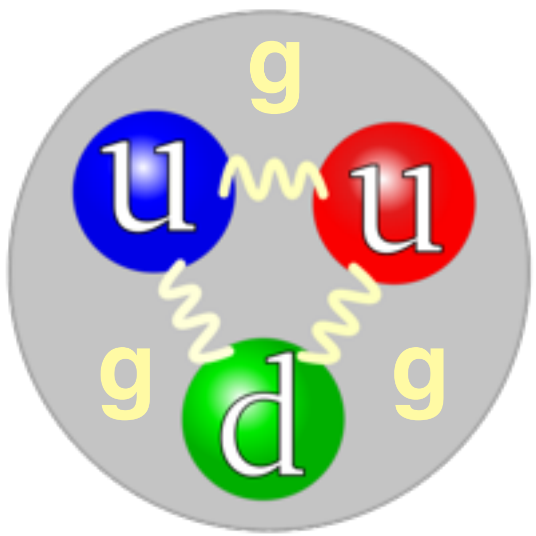


Neutron

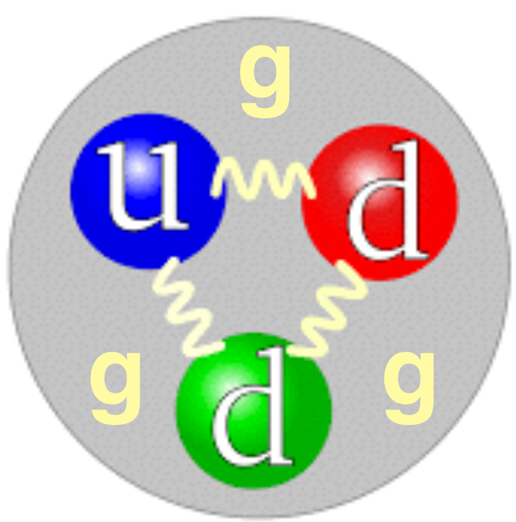
Image Source: Wikipedia



They are held together by the gluon (strong force carrier)

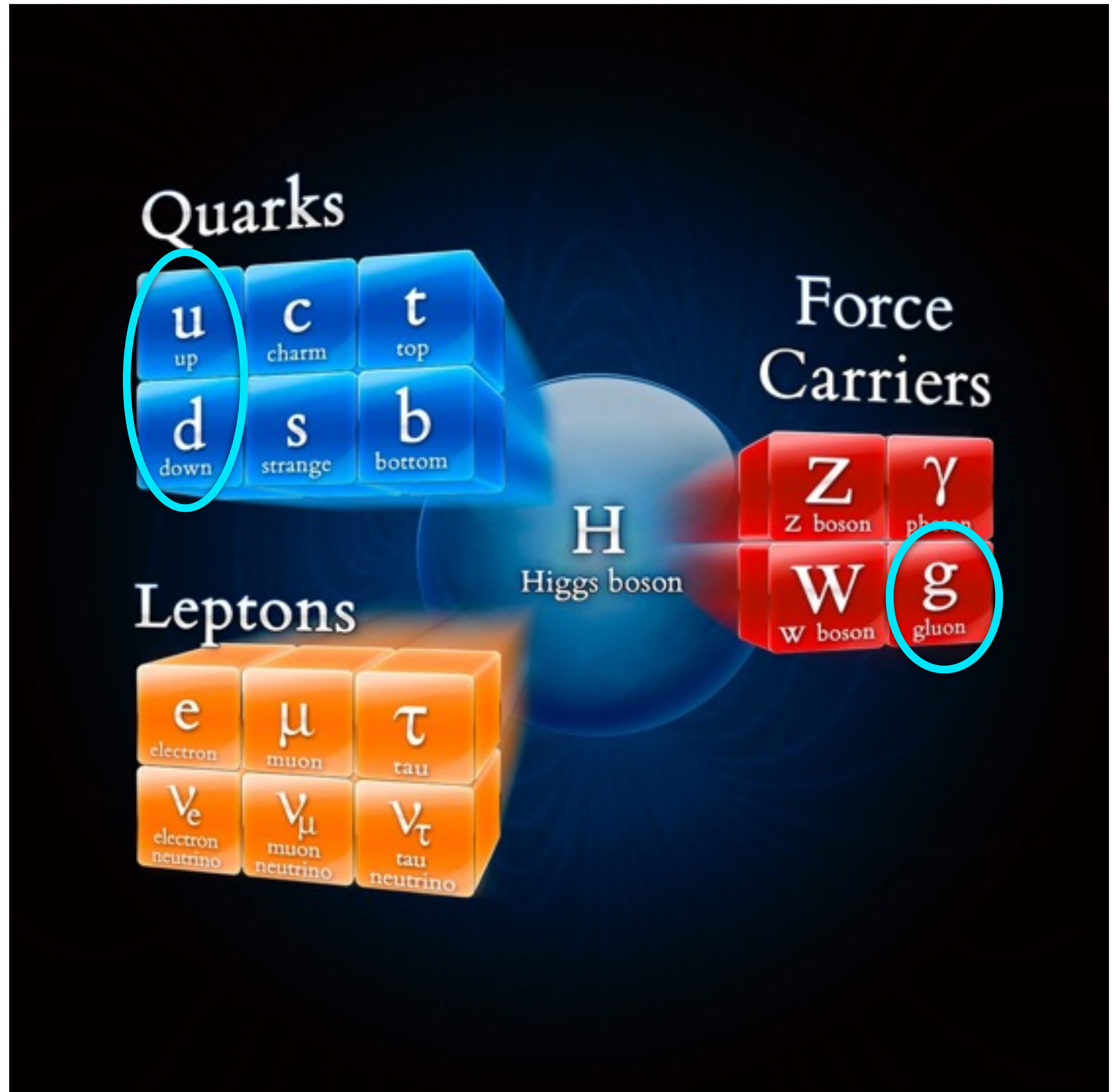


Proton

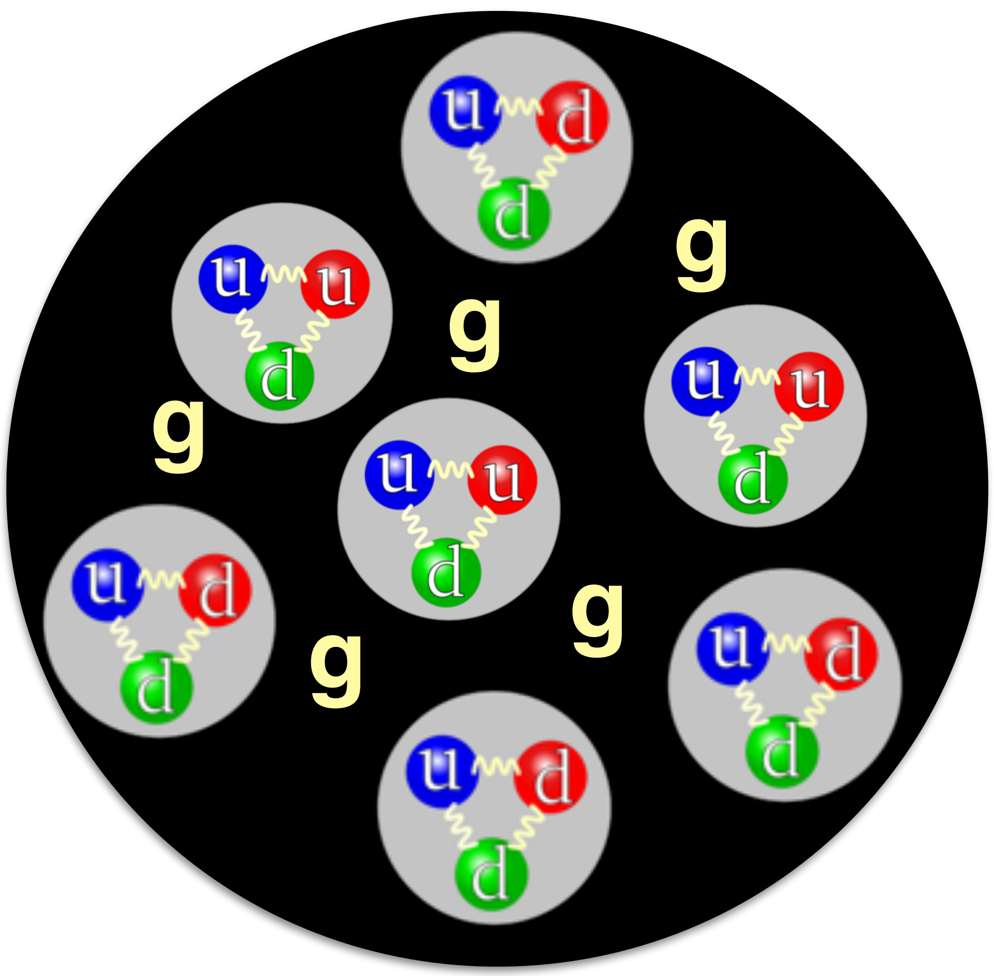


Neutron

Image Source: Wikipedia



Residual strong force keeps protons and neutrons bound together



Nucleus

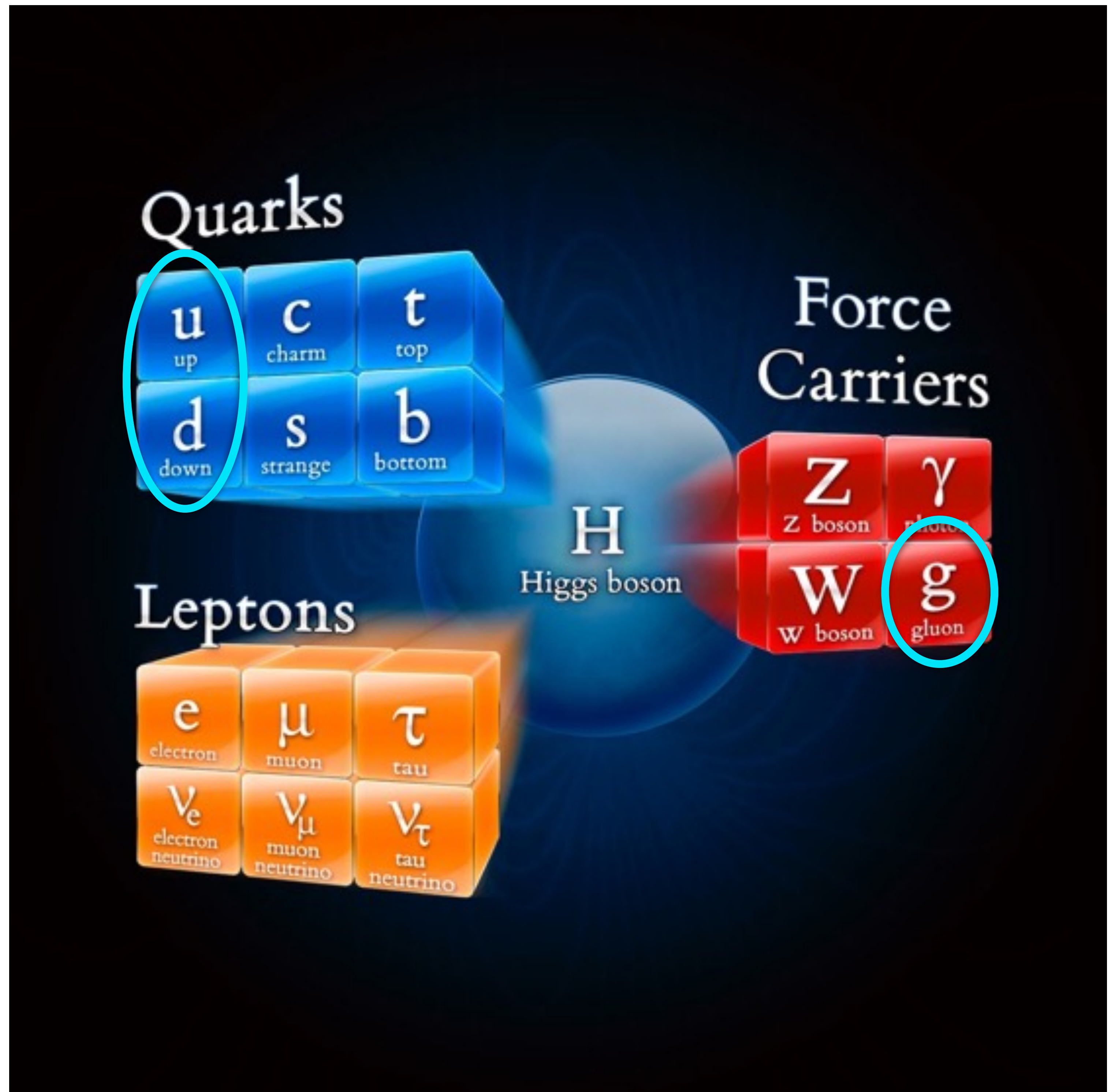
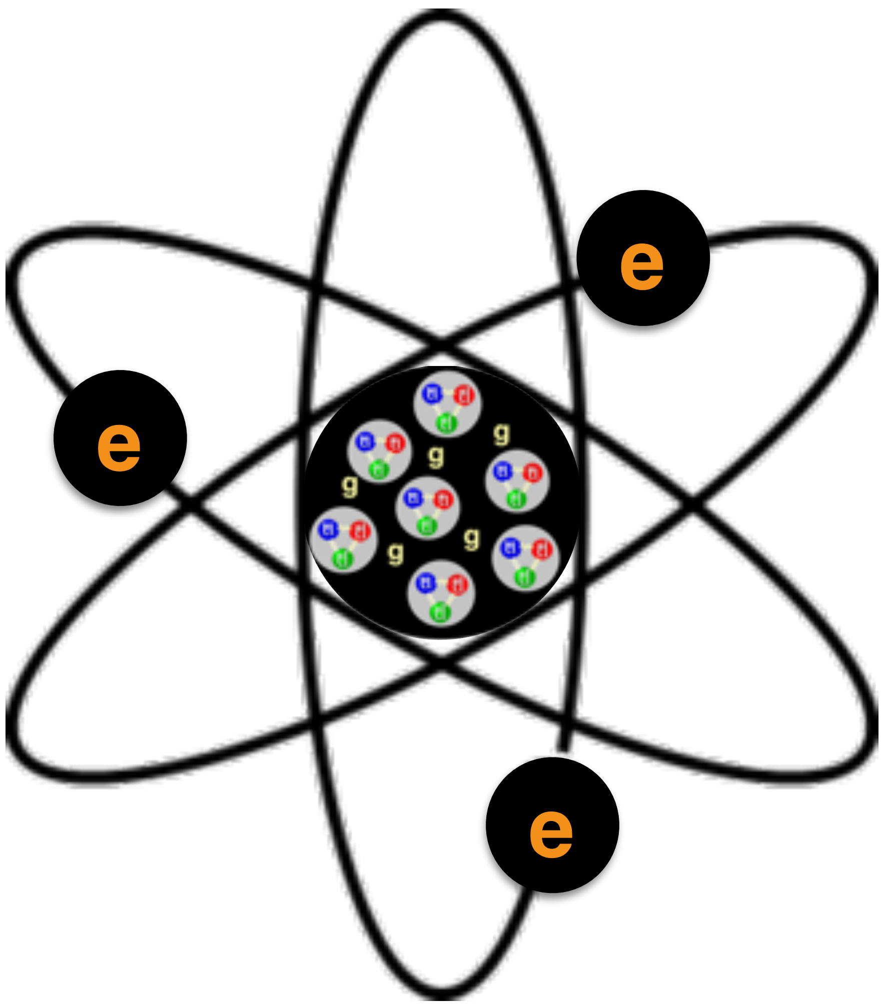


Image Source: Wikipedia

And electrons are bound to nuclei by photons (electromagnetic force carrier)



Atom

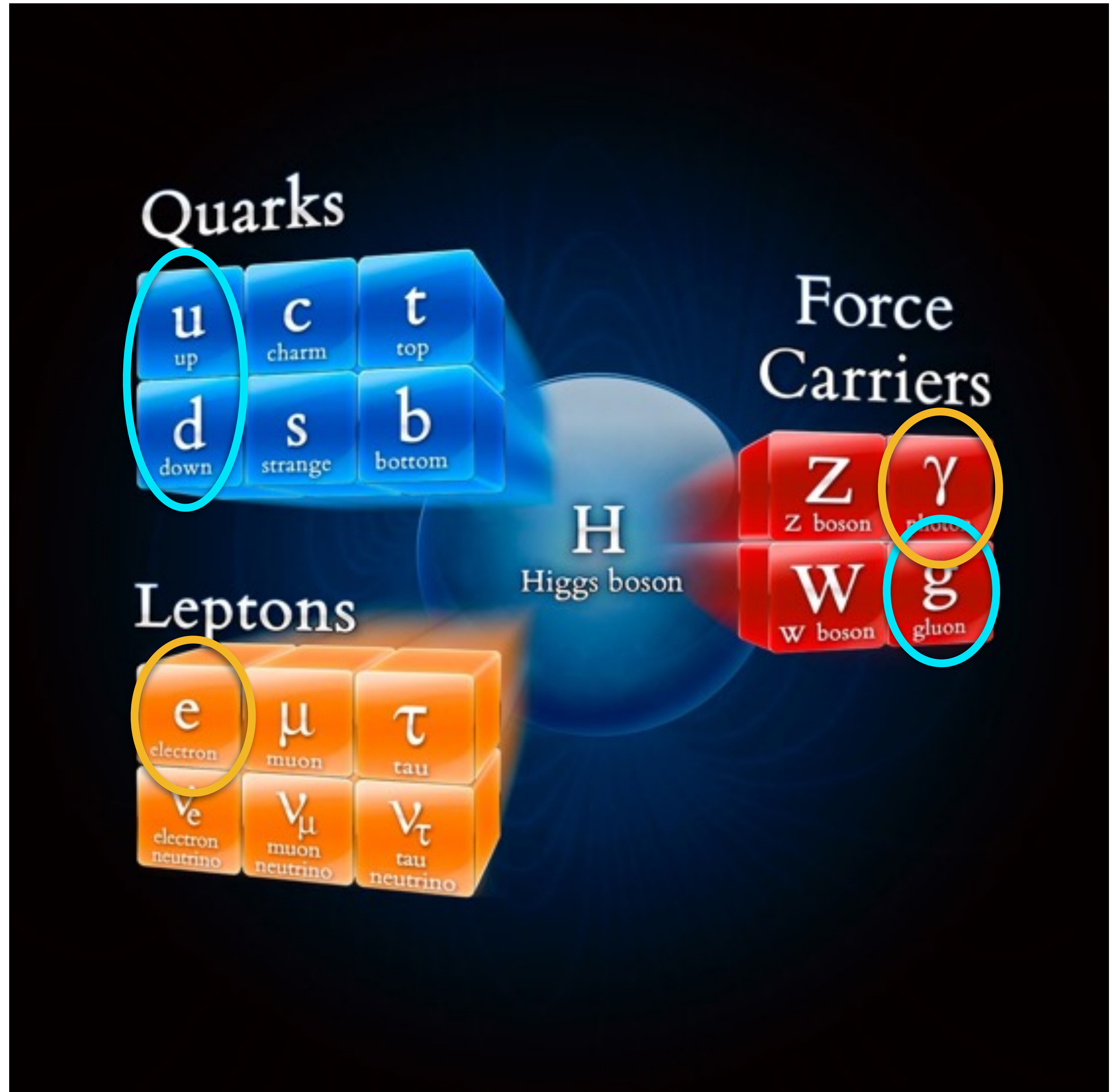
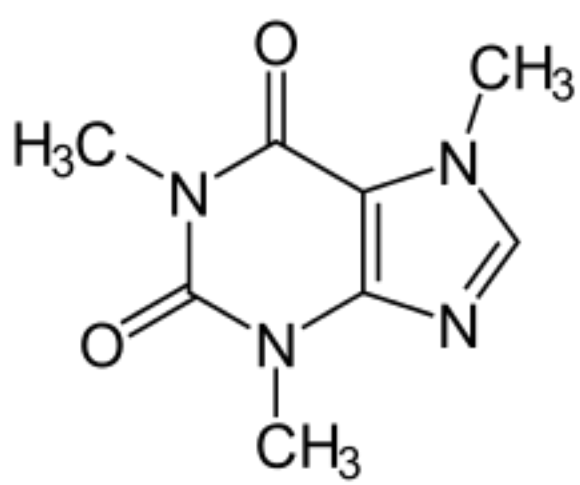
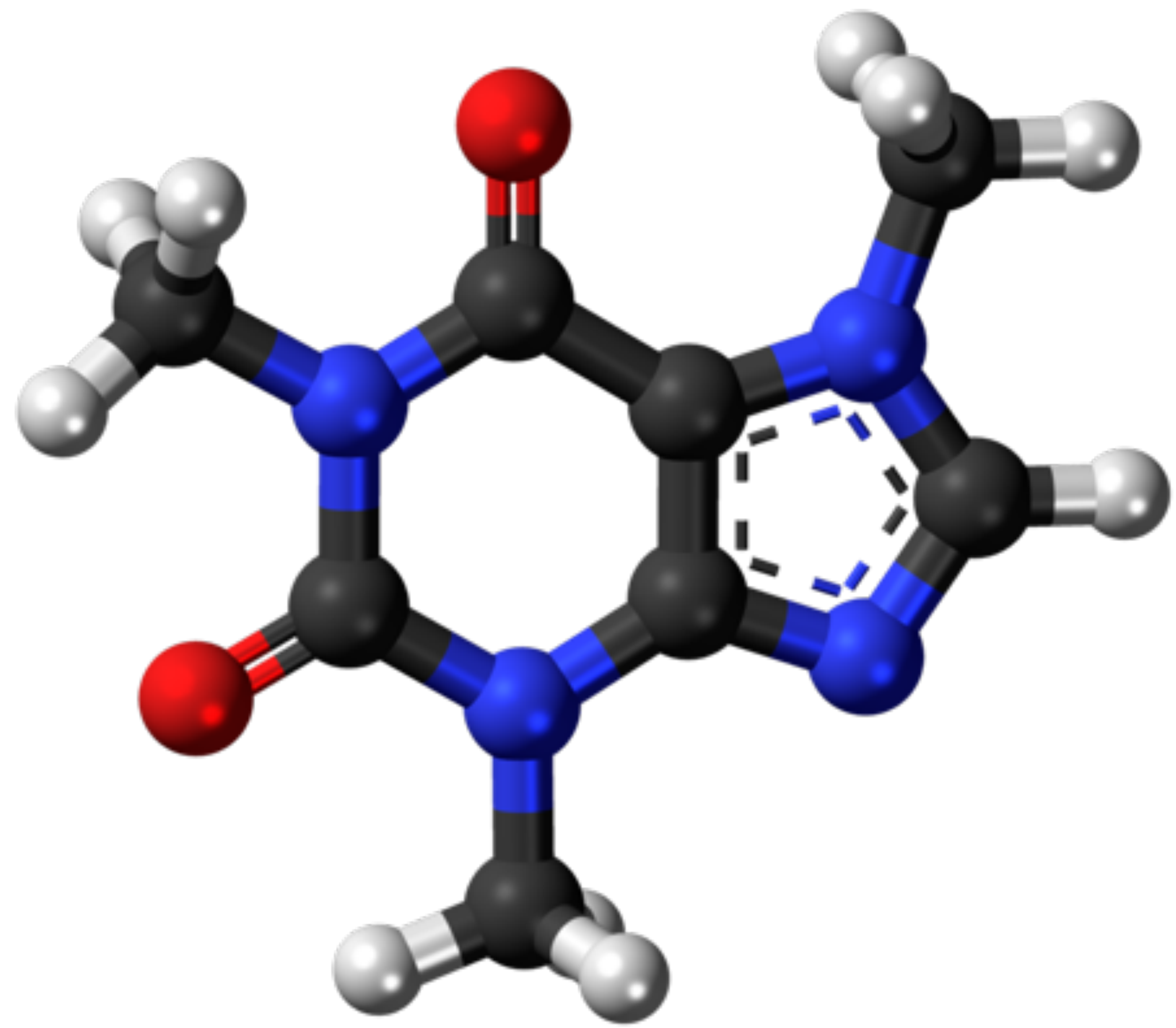


Image Source: Wikipedia

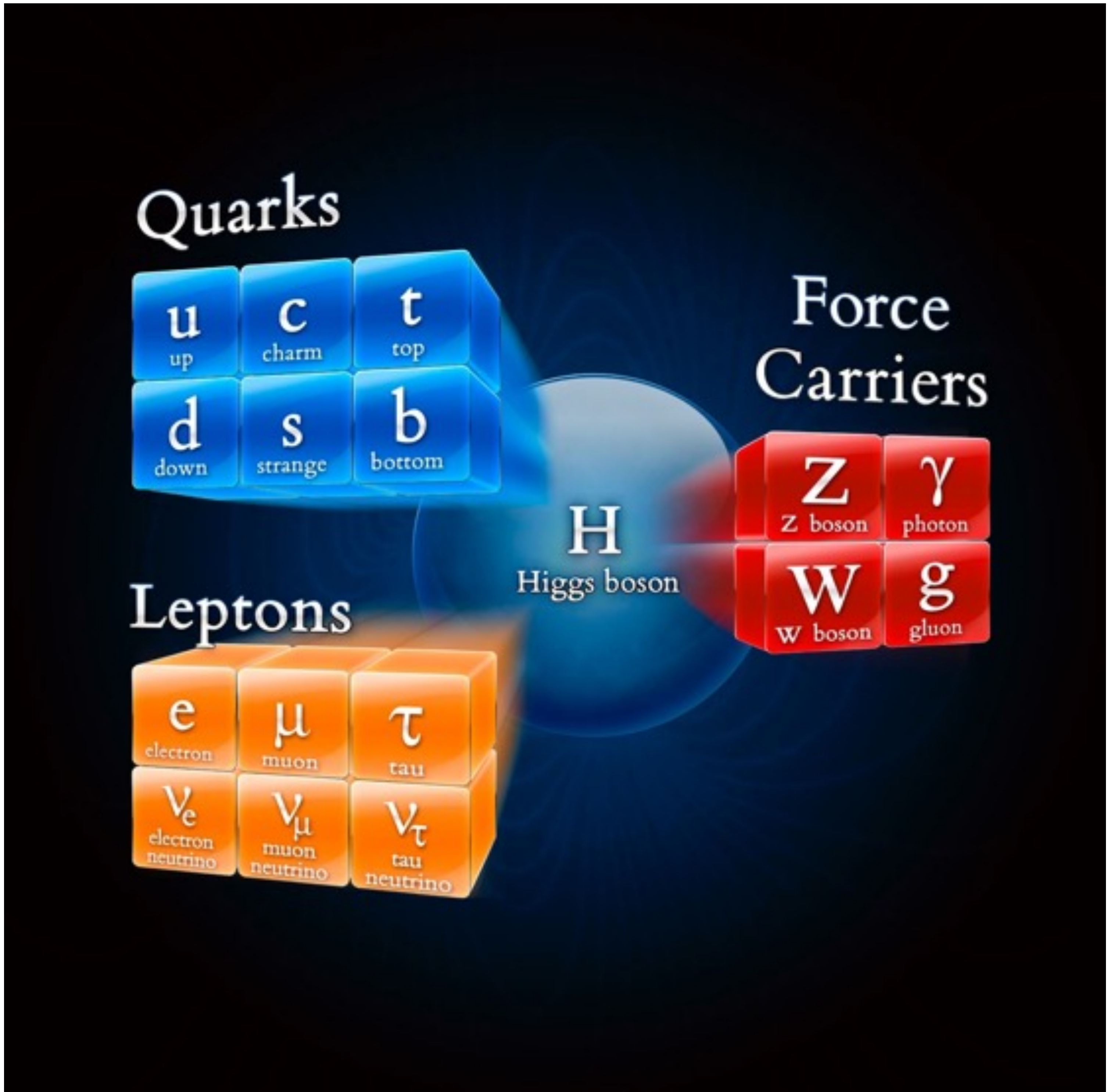
These atoms interact electromagnetically to give us the chemicals that make up our world





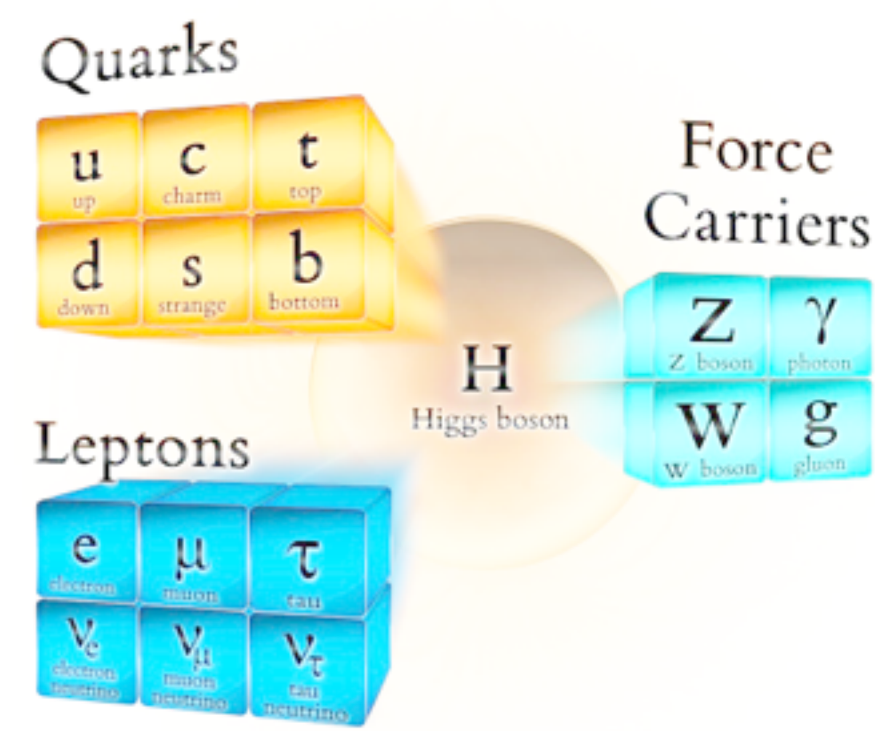
Images: Wikipedia, "Caffeine"

But what about the rest of the elementary particles?



+

Anti-matter



*Disclaimer: Some of these particles (e.g., the photon) are their own anti-particles.

At the beginning of the universe, these particles existed in abundance!

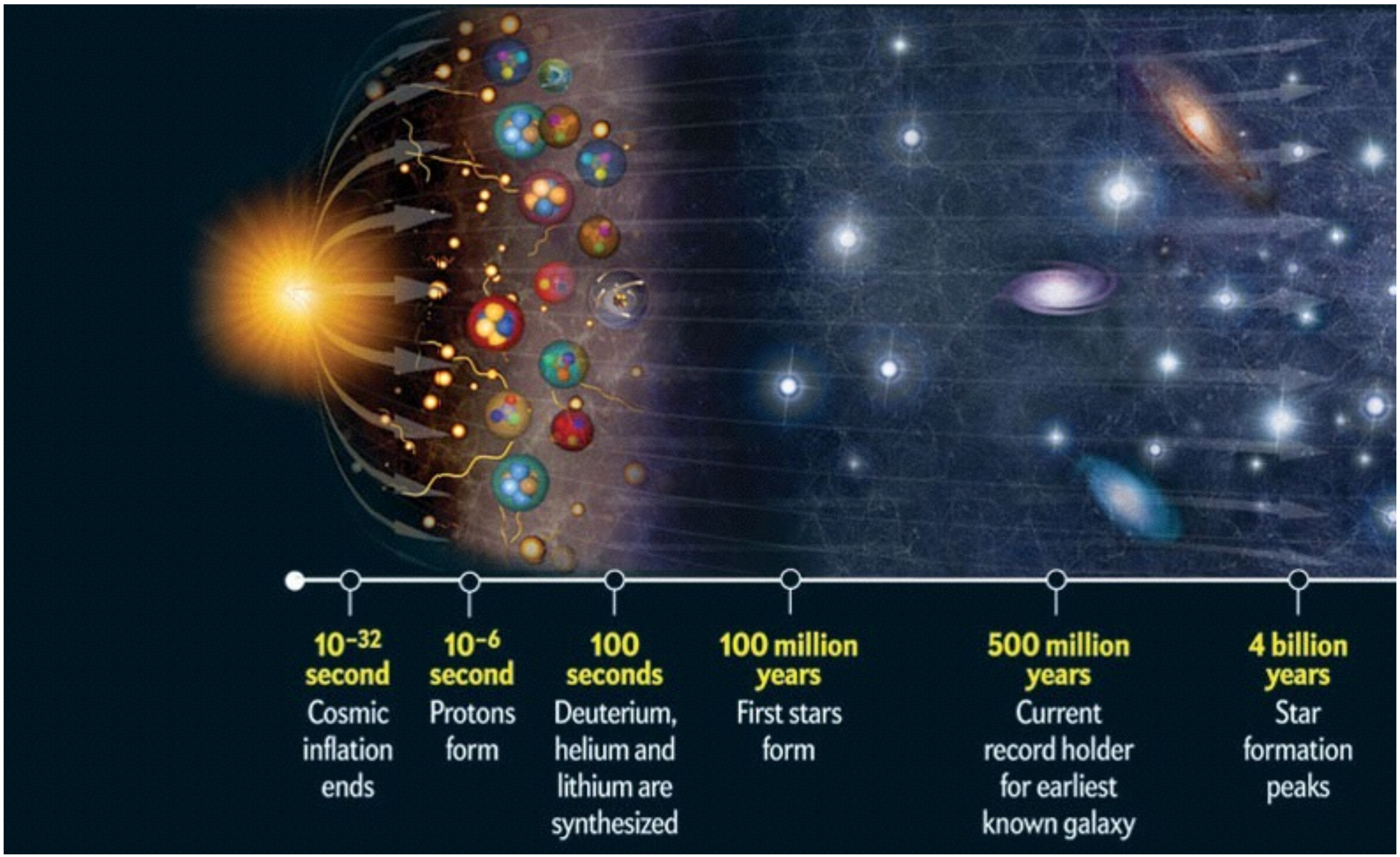
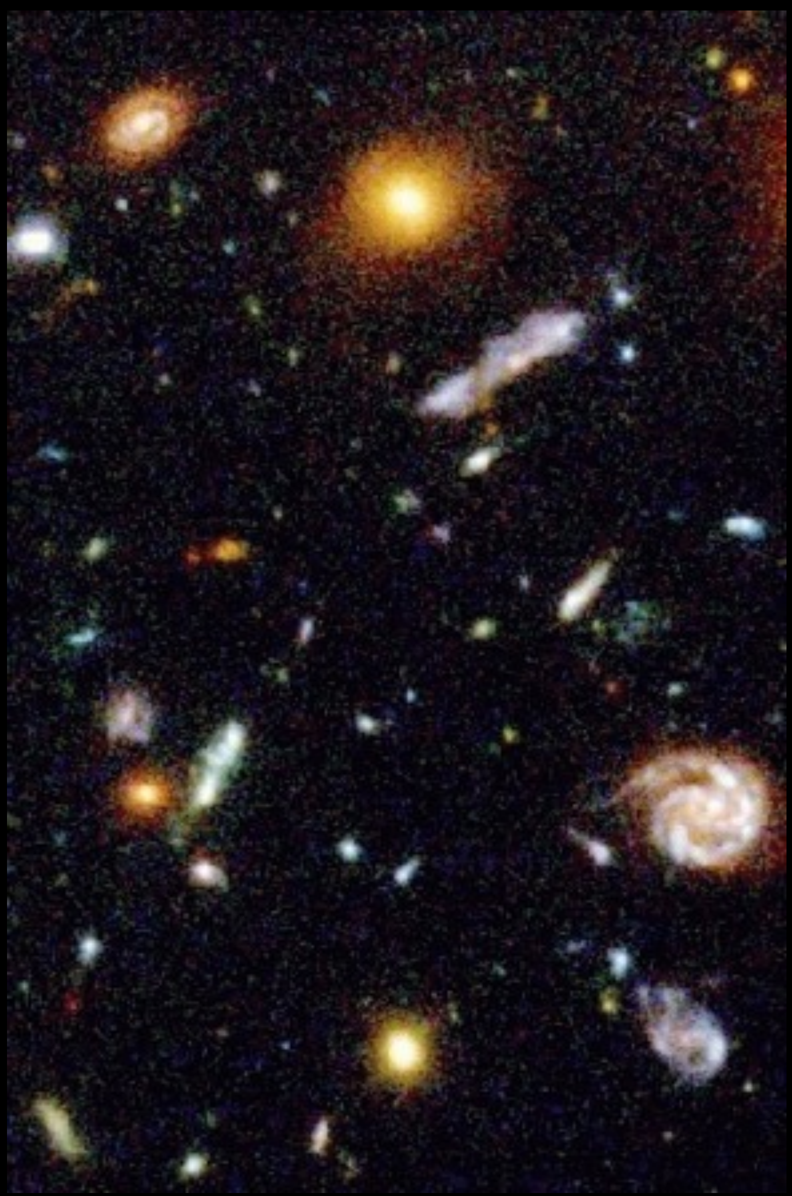
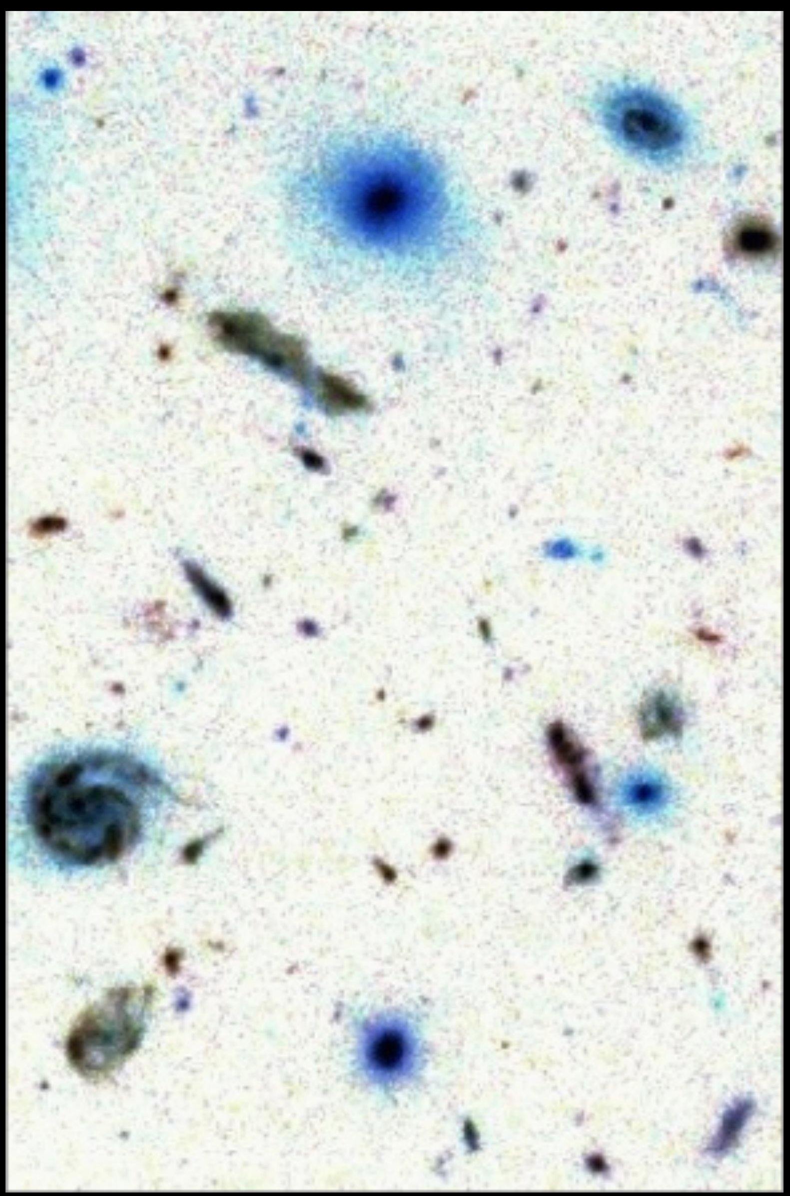


Image Source: Astroblogs: "Waarin dijt het heelal uit?"

Matter and anti-matter almost completely annihilated

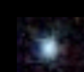


10,000,000,001



10,000,000,000

Leaving behind a universe dominated by matter



1 0

And as the universe cooled down, heavier, more exotic particles were unstable

…and **they decayed away**…

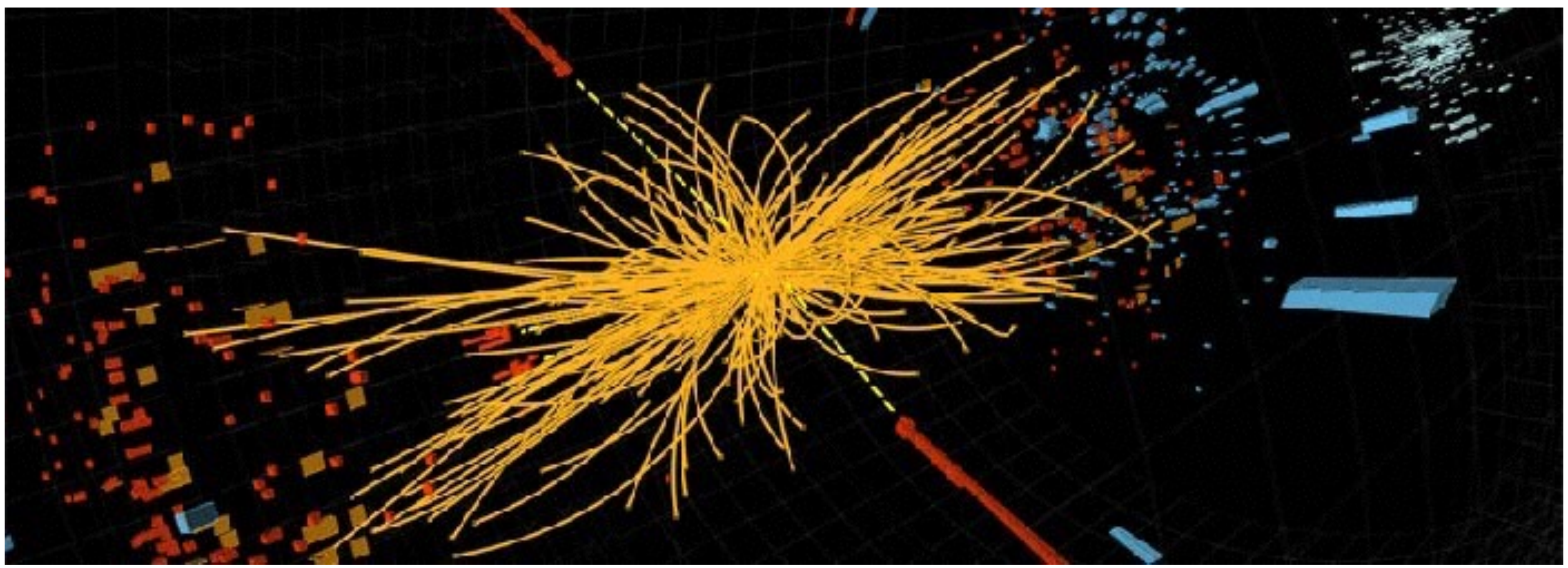


Image Source: CERN, Simulated CMS Event Display

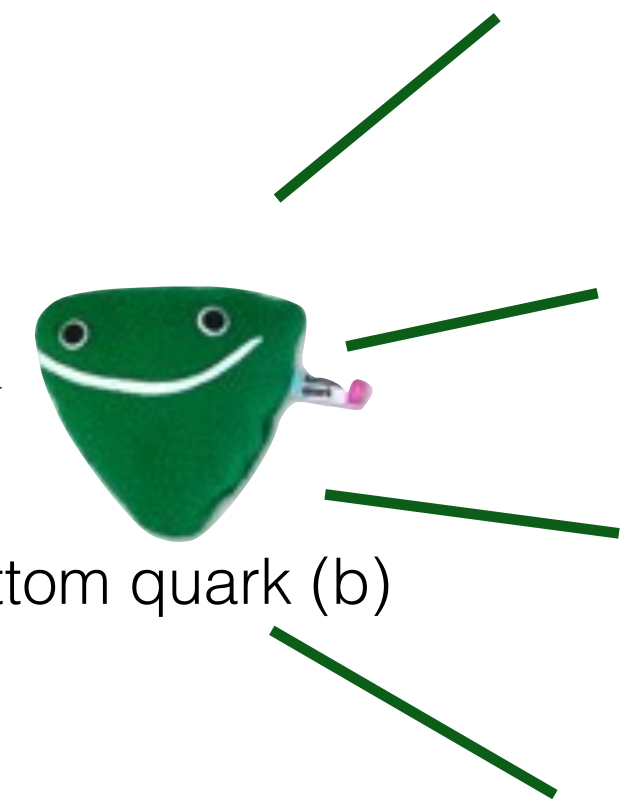
Disclaimer: This is a simulated Higgs production event in proton-proton collisions at CMS. Some of the final-states of particles represented by this image are probably muons. Should be considered for illustrative purposes only.

…until all that was left were the familiar, lighter particles!

Elementary particles aren't composed of anything smaller

They **can't simply 'break apart'** when they decay. They must ***change identity*** and shed excess energy (as particles).

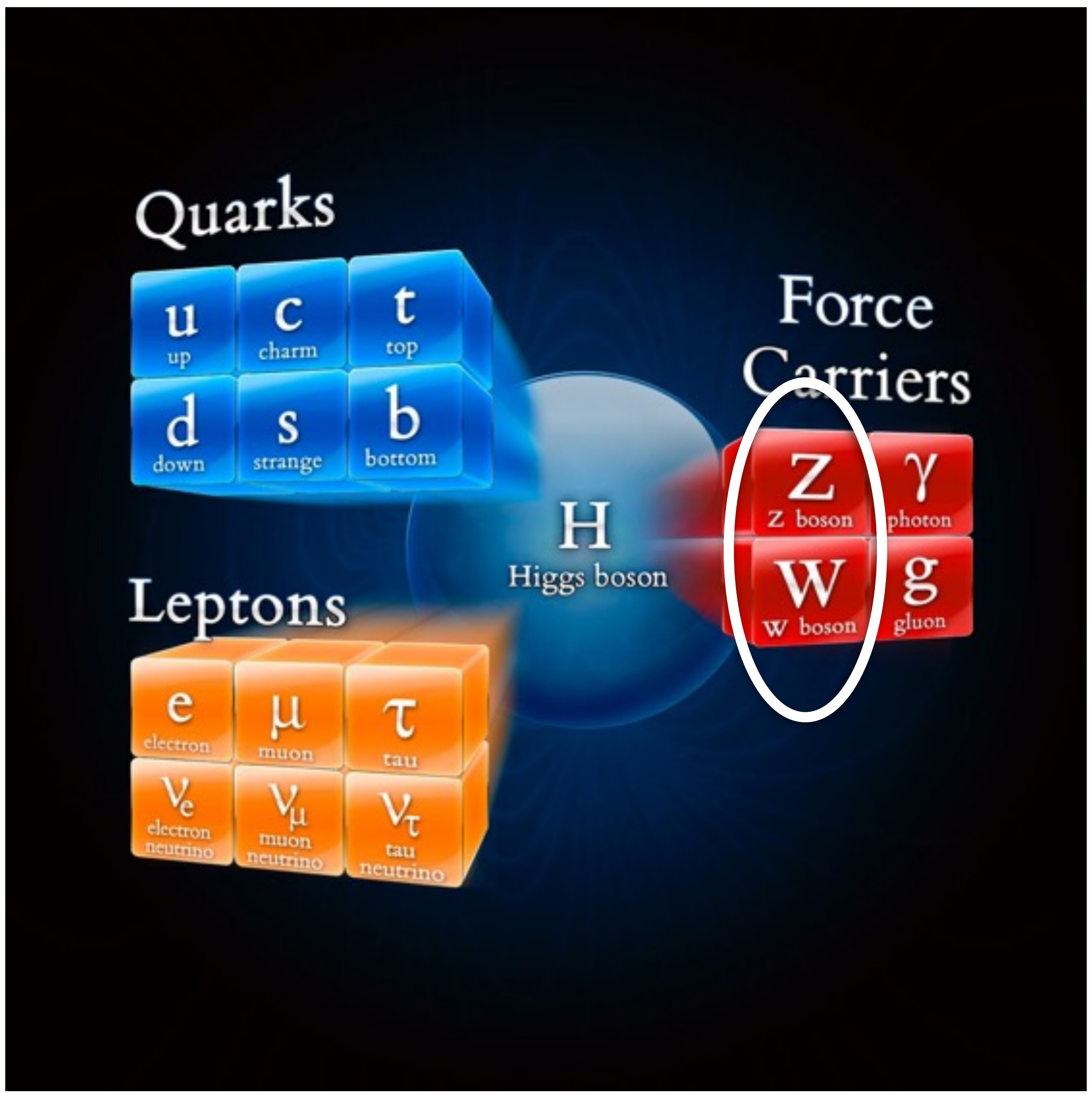
top quark (t)

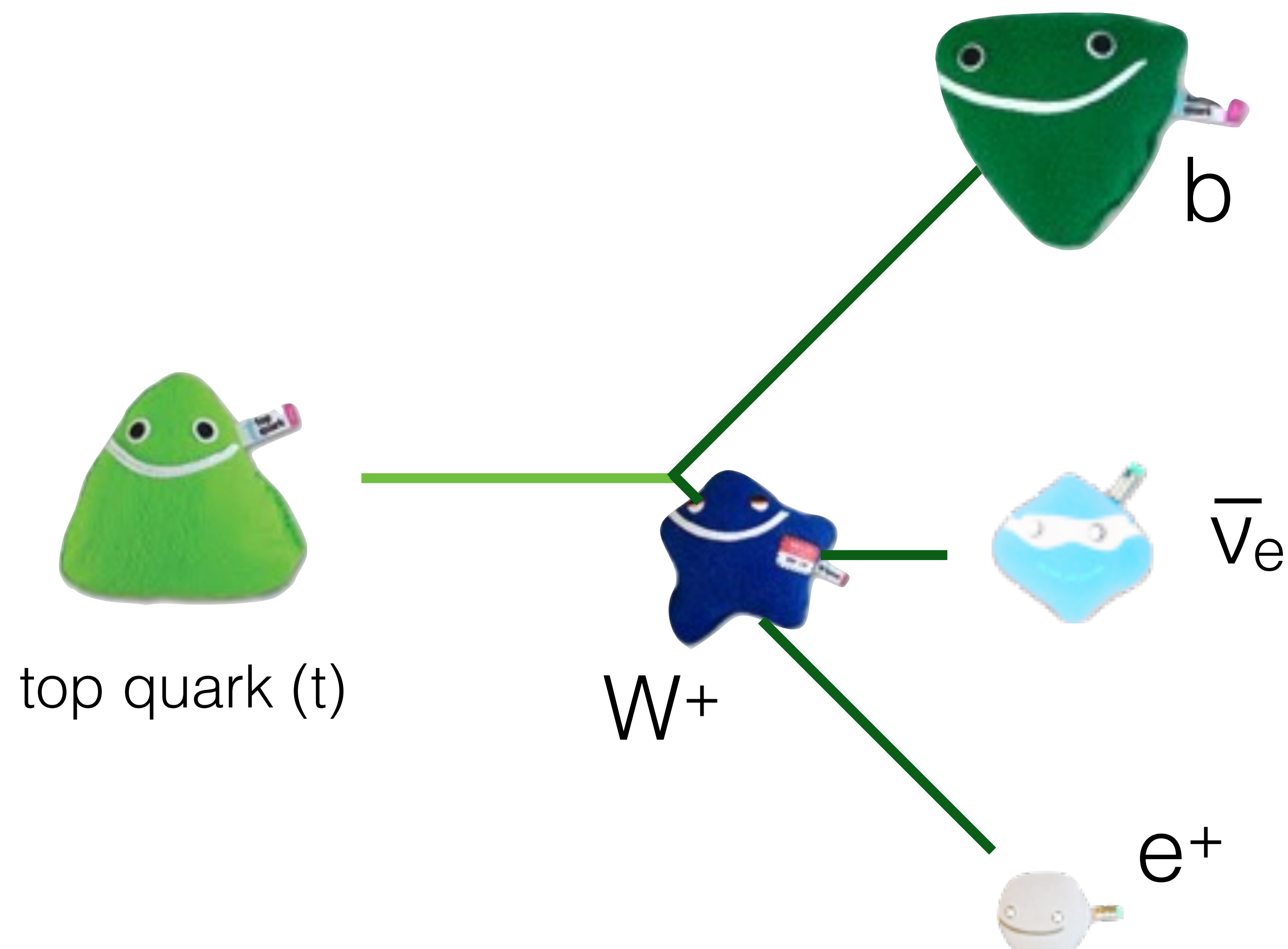


bottom quark (b)

*__Disclaimer__: Except for the top quark, quarks do not exist outside of bound states. In general, quark flavor-changing interactions would take place inside of a meson or baryon.

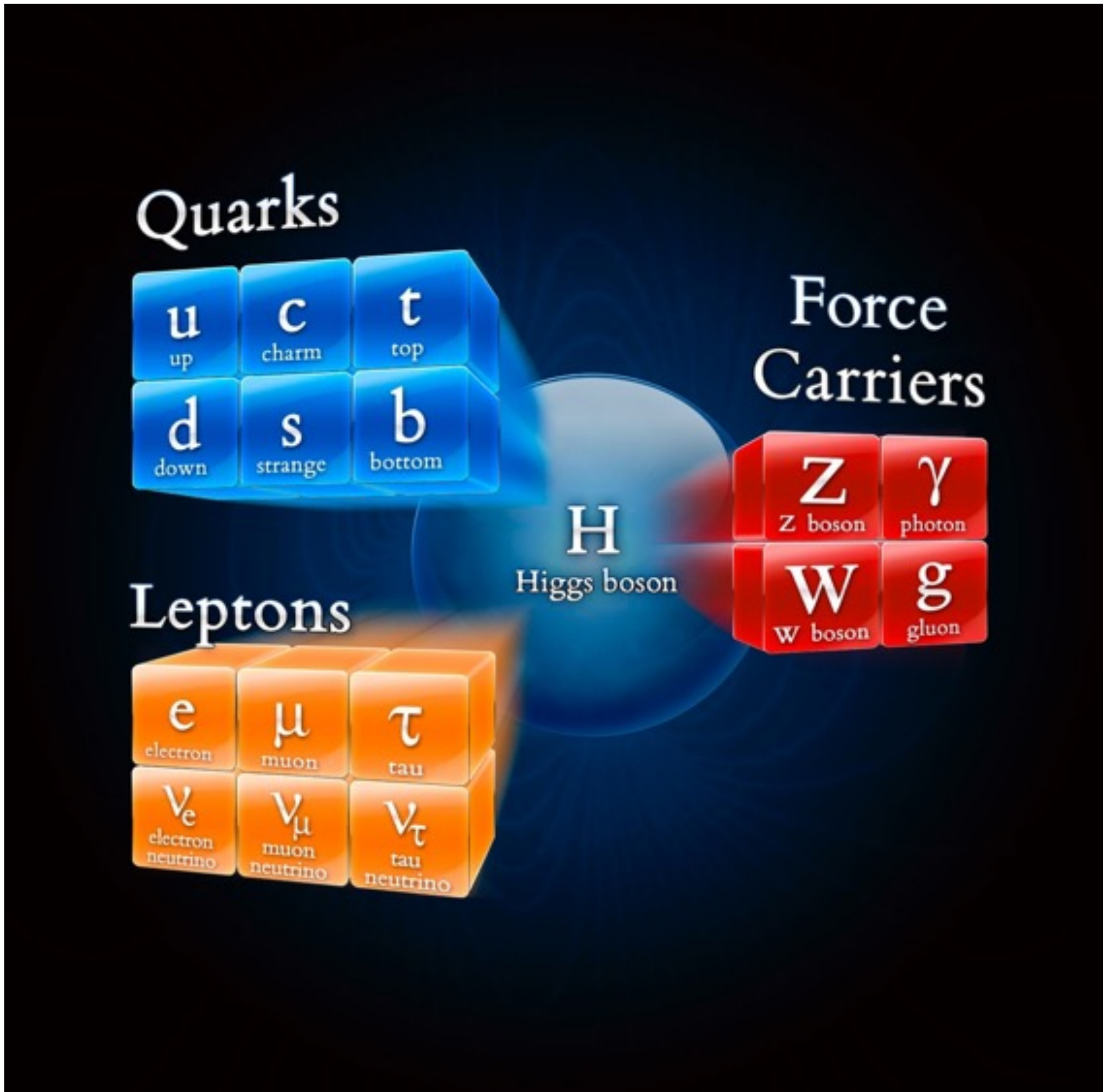
This kind of identity-swapping is possible through the **weak force**

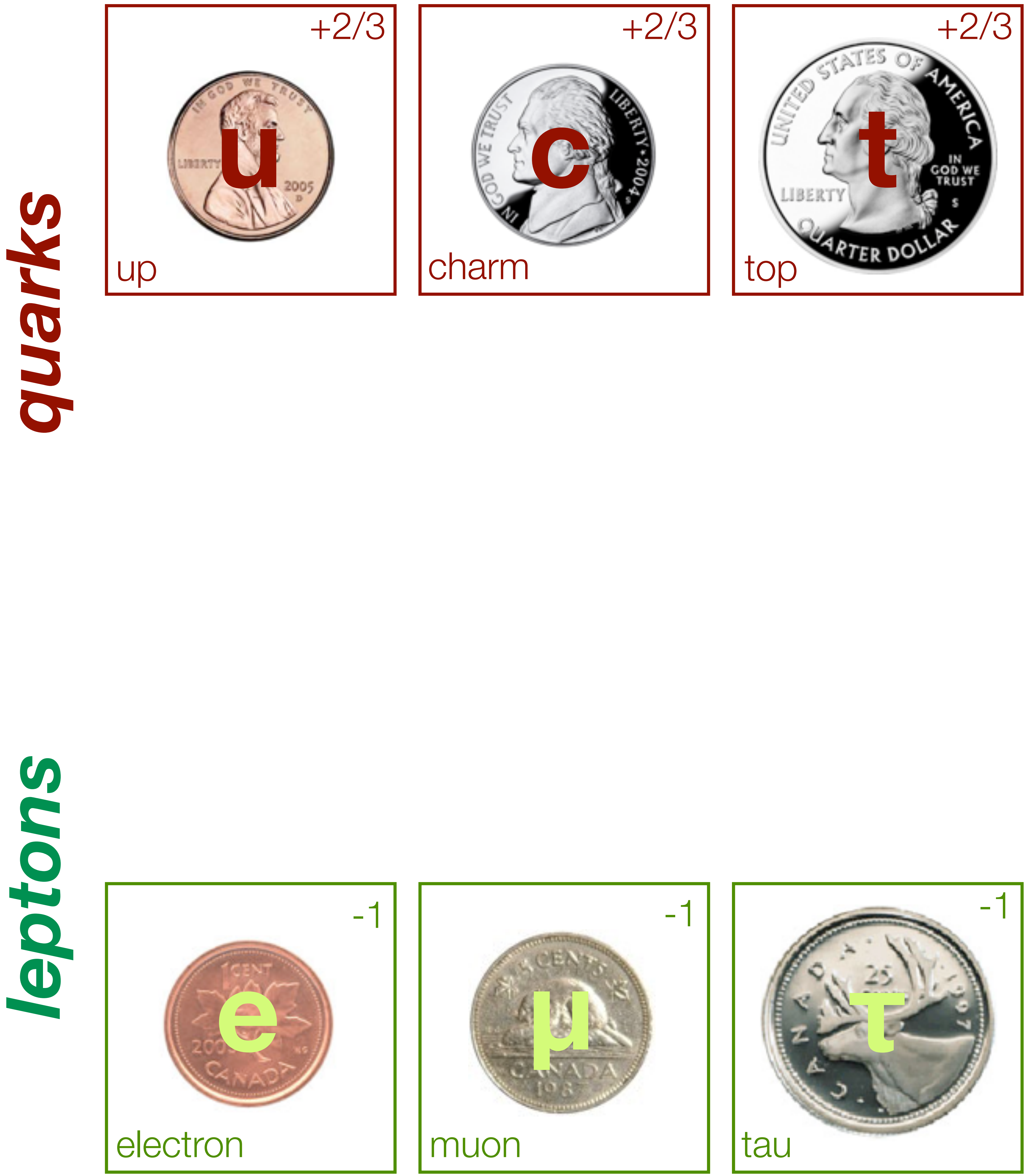




And **neutrinos** are the weak force's attendant!

So going back to these…



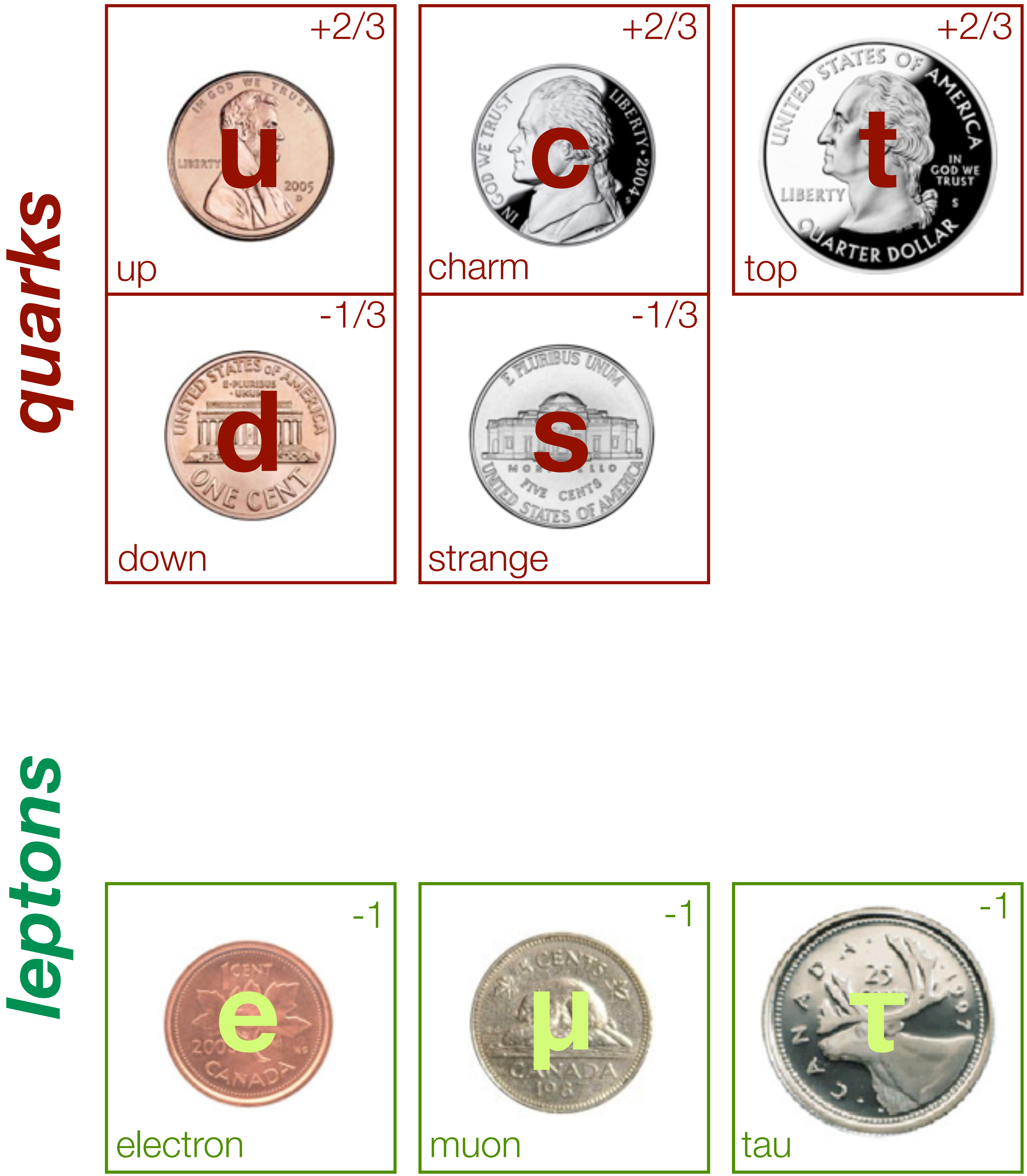


All of **matter is made up of ‘coin’-like particles**

Each particle can be **‘flipped’** by **weak interactions**

All of **matter is made up of ‘coin’-like particles**

Each particle can be **‘flipped’** by **weak interactions**

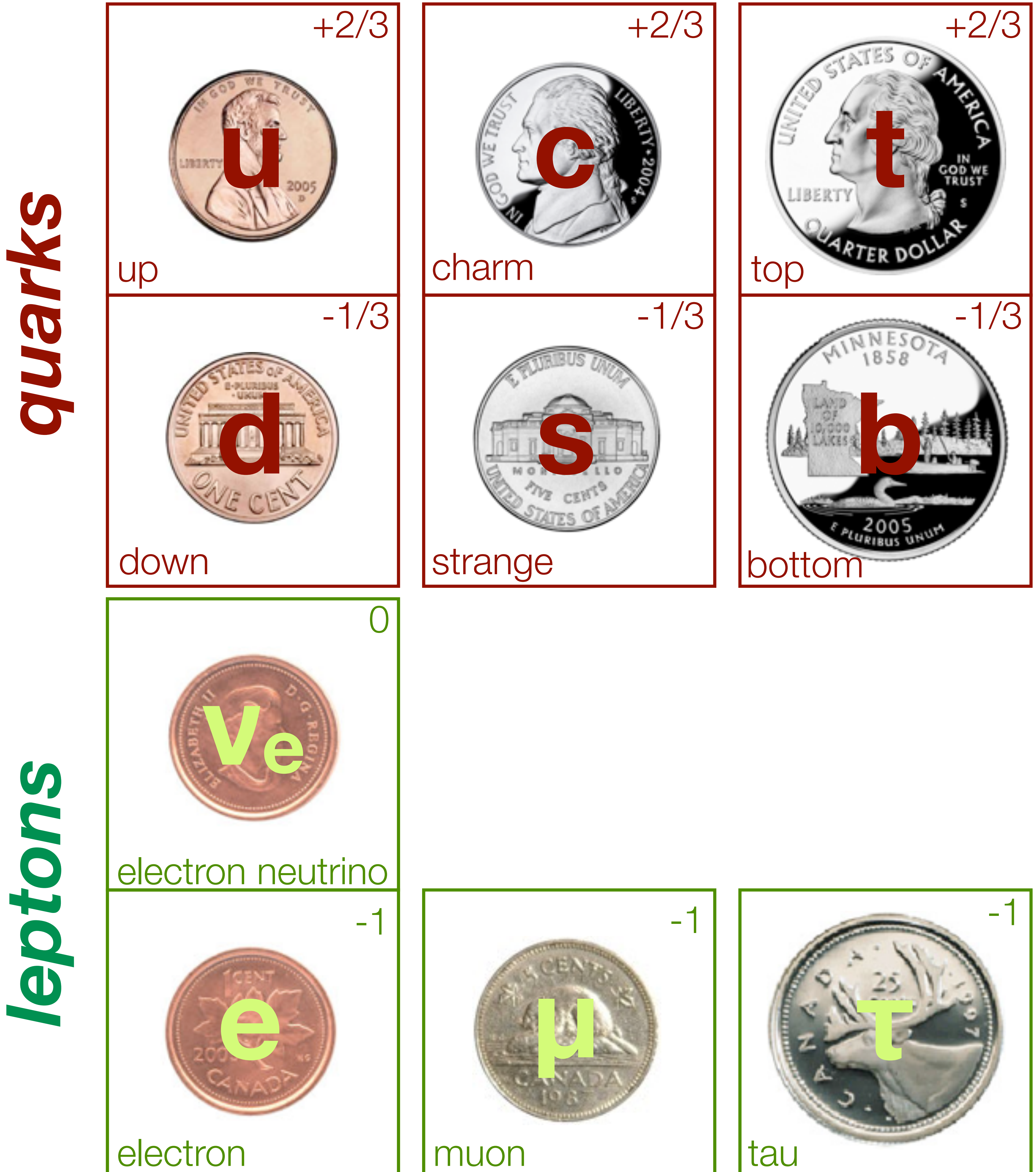


All of **matter is made up of ‘coin’-like particles**

Each particle can be **‘flipped’** by **weak interactions**

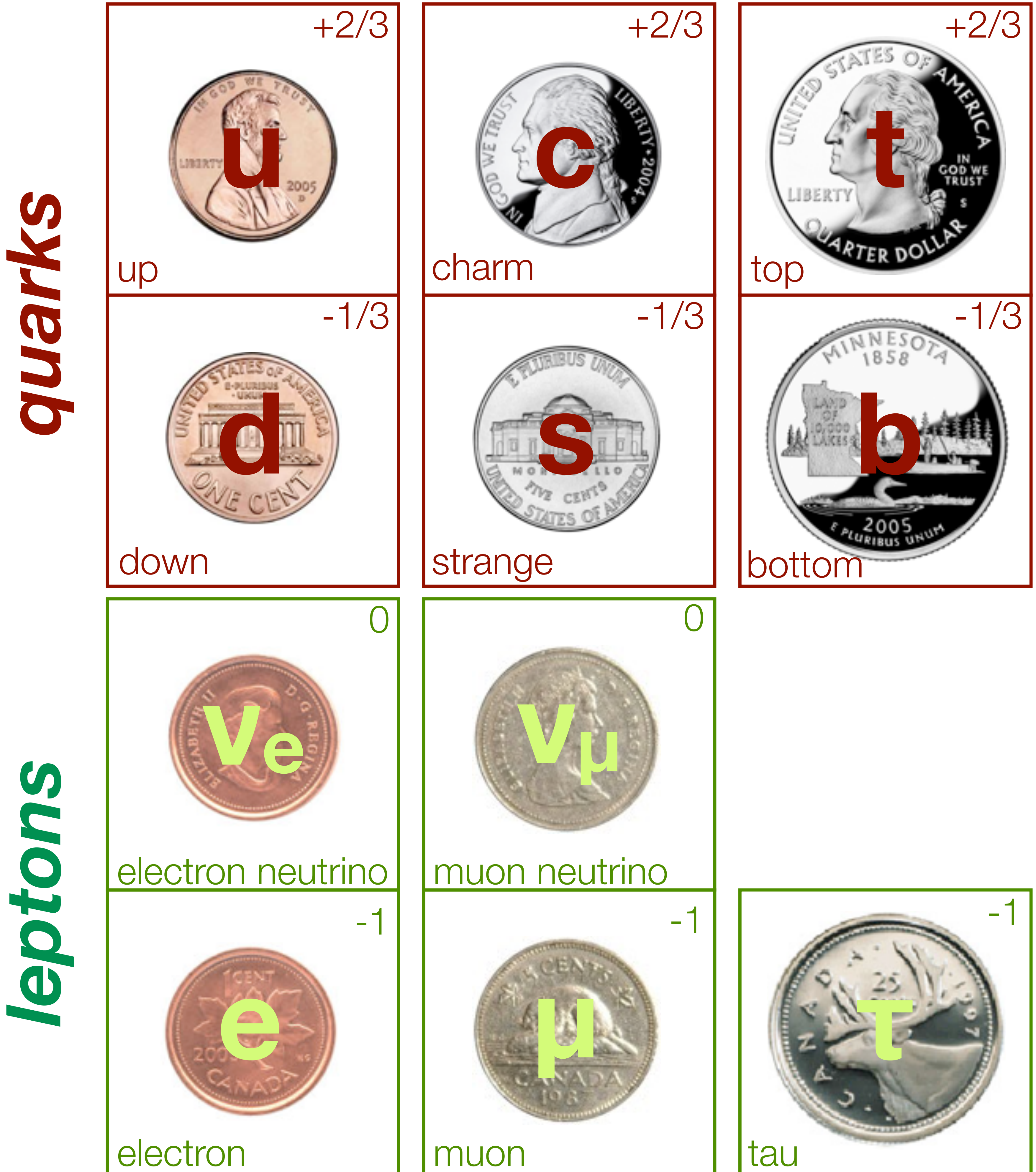
All of **matter is made up of 'coin'-like particles**

Each particle can be **'flipped'** by **weak interactions**



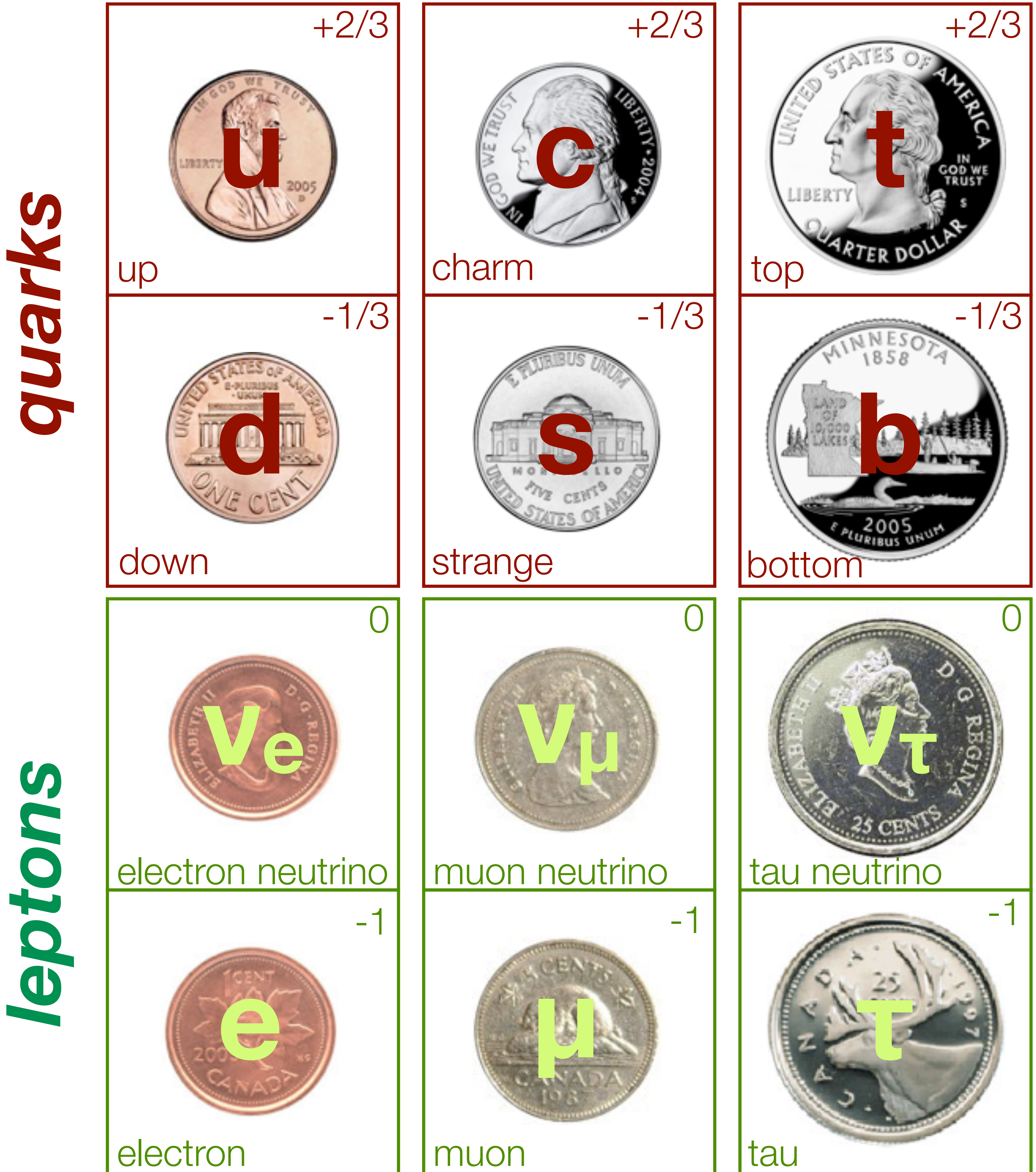
All of **matter is made up of ‘coin’-like particles**

Each particle can be **‘flipped’** by **weak interactions**



All of **matter is made up of 'coin'-like particles**

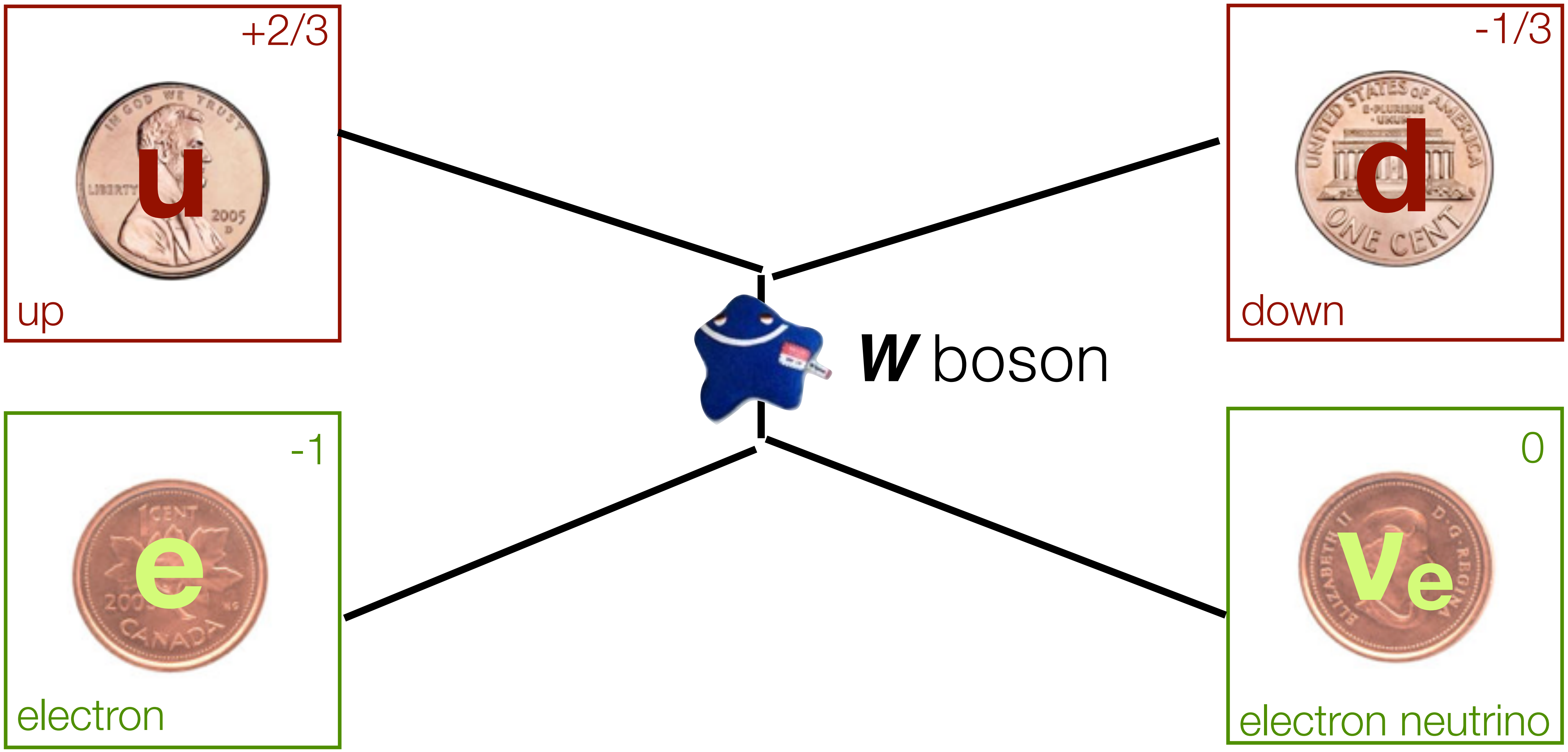
Each particle can be **'flipped'** by **weak interactions**



All of **matter is made up of 'coin'-like particles**

Each particle can be **'flipped'** by **weak interactions**

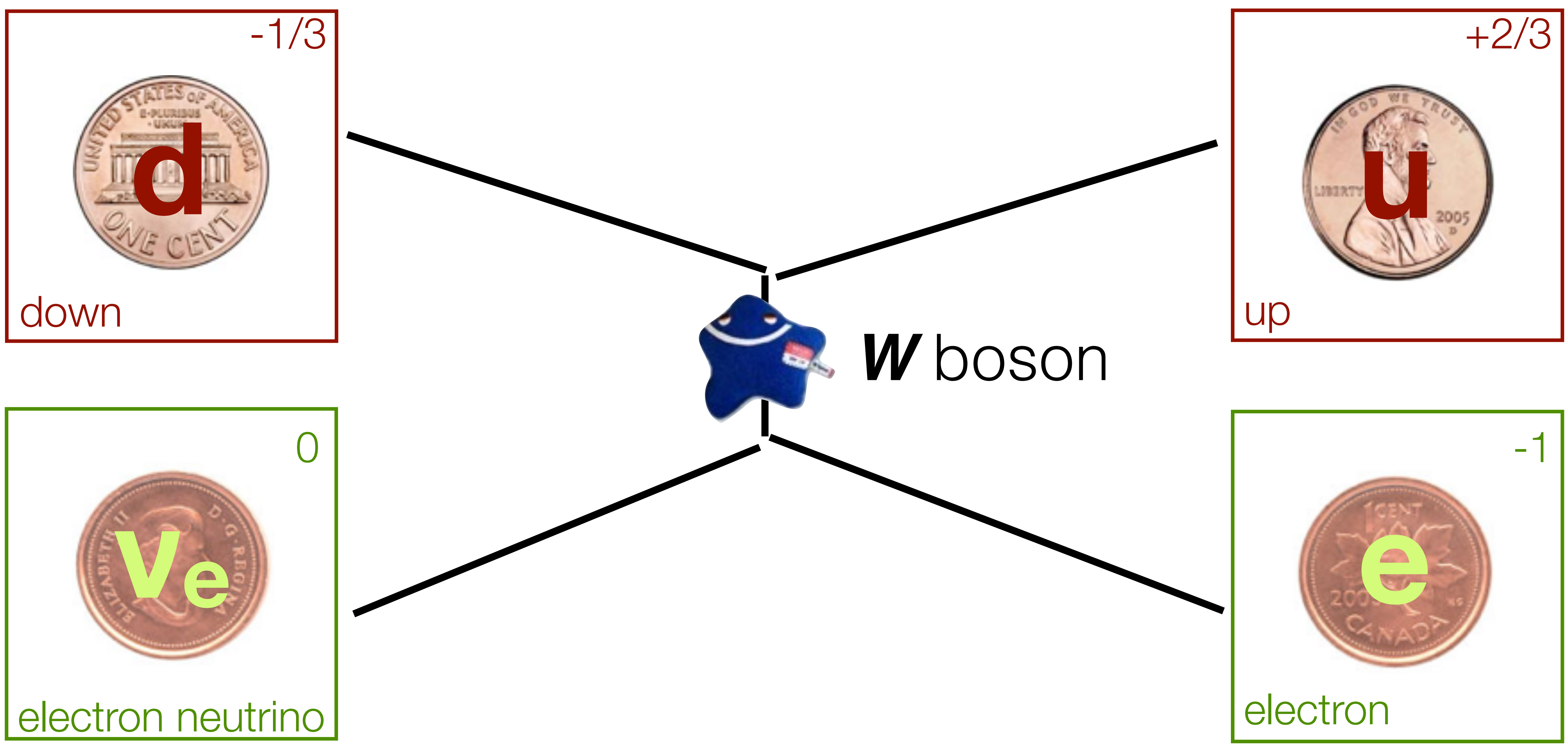
But these interactions cannot happen alone



An up quark can be flipped into a down quark —
but, *e.g.*, an electron must be flipped into a neutrino as well.

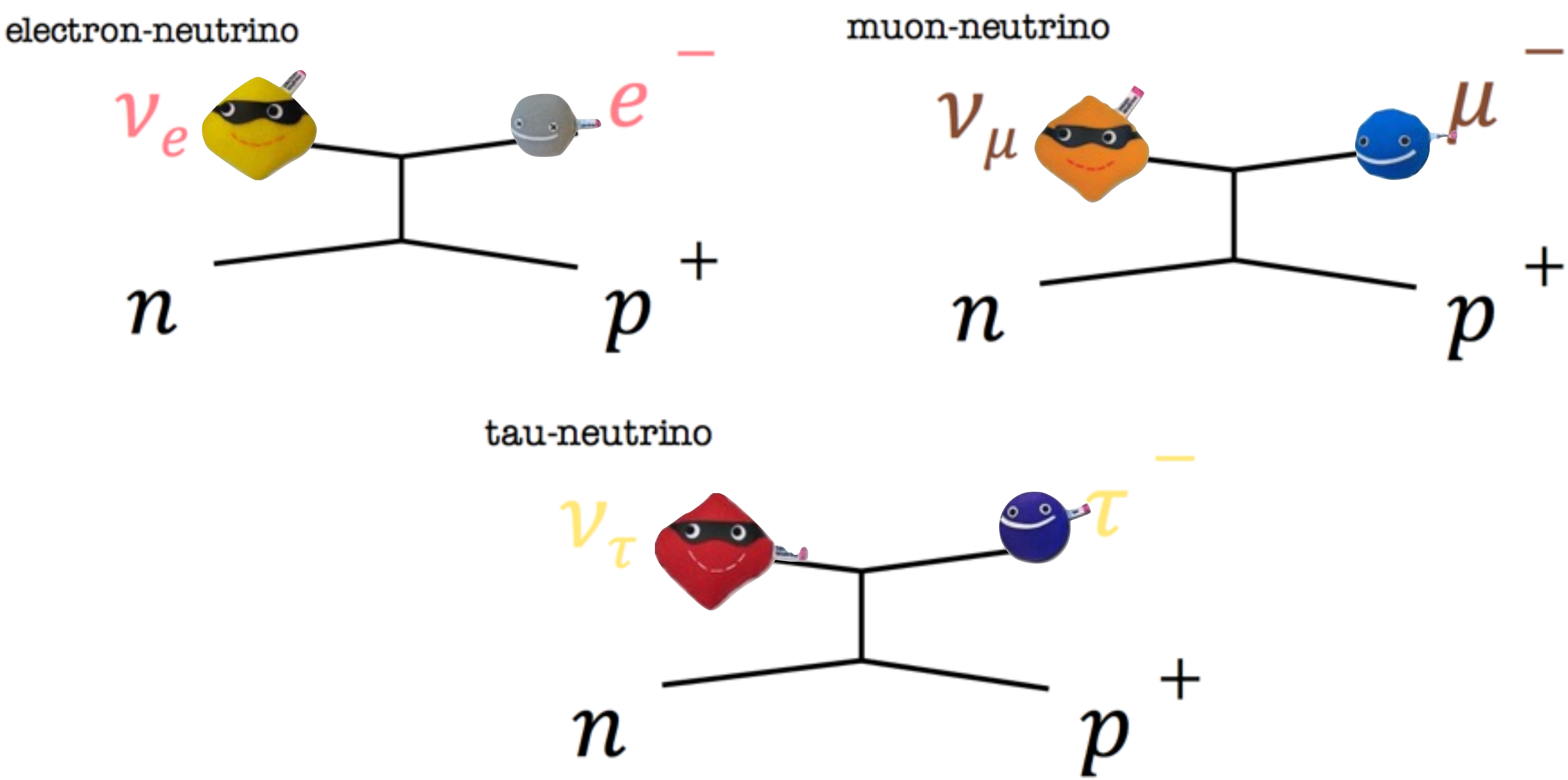
Neutrinos are very frequently involved!

In fact, we can use neutrinos to force these processes to go in reverse



This is the basis of neutrino detectors!

In such interactions, neutrino flavor states will change into the particle they're named after



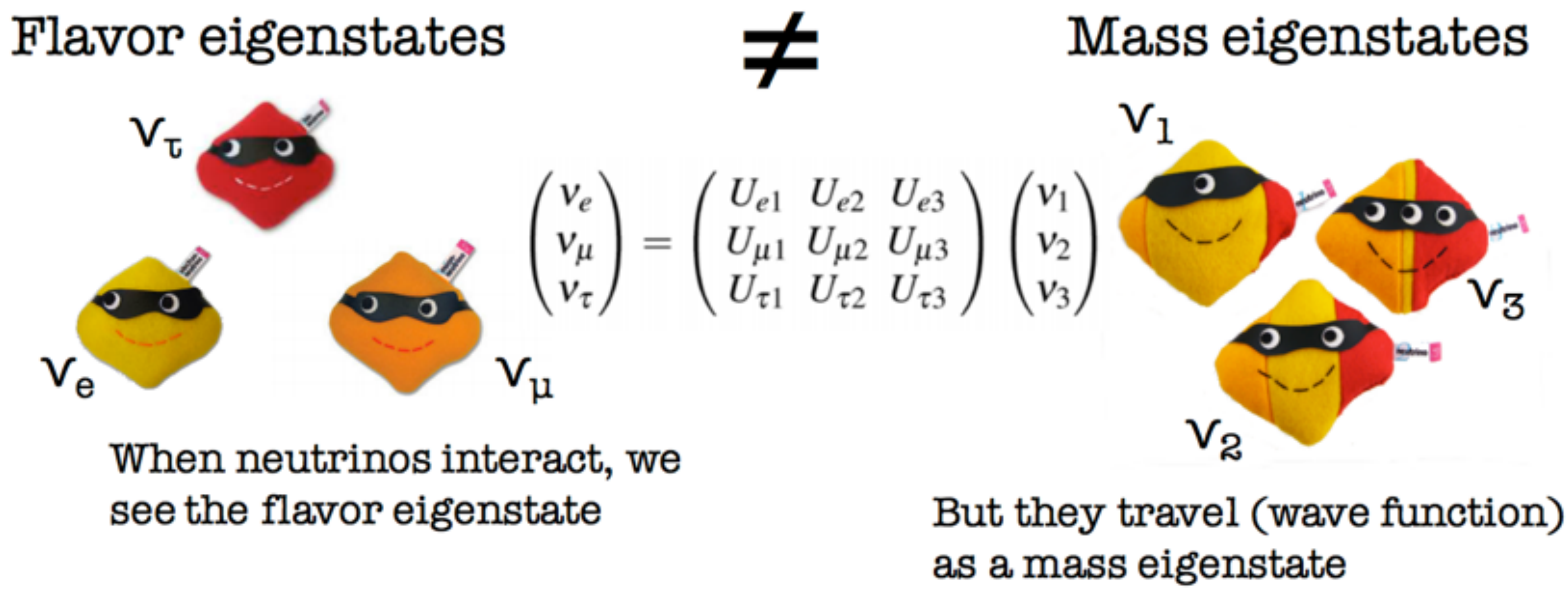
(Diagrams from Anne Schukraft's talk on June 16)

Neutrinos can change identity without involving other particles

As neutrinos travel, they ***oscillate*** through three identities: electron neutrino, muon neutrino, and tau neutrino.

This means that an electron neutrino created in the sun might be detected here on earth as a muon neutrino!

This is because neutrino flavor states are composed of different mass states



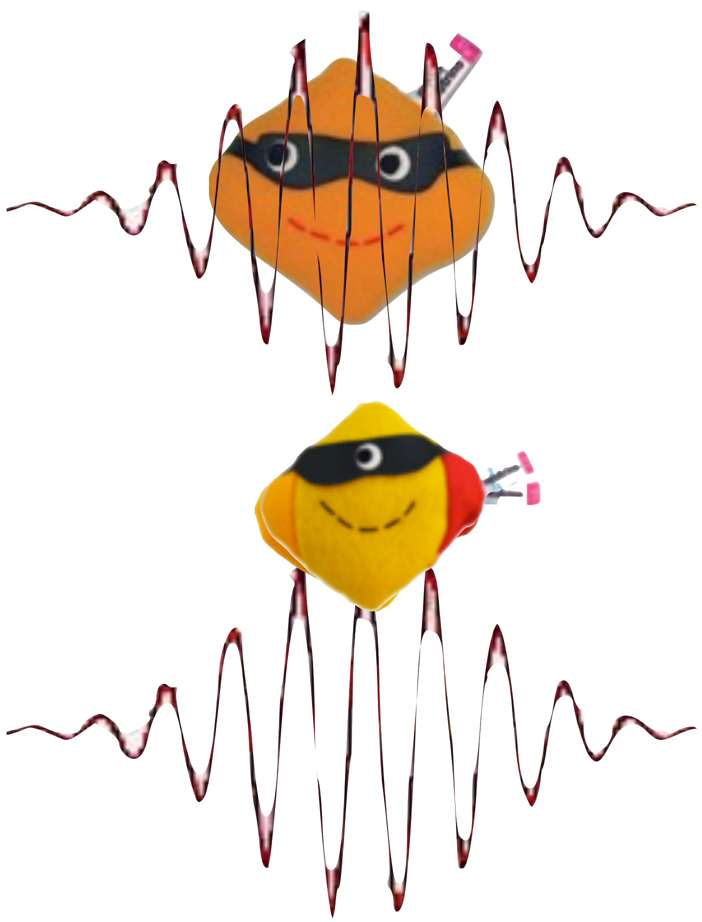
(Recall that $p = mv$. The same p applied to three different m will give three different v!)

(Graphics from Anne Schukraft's talk on June 16)

Let’s say that we start off with a muon neutrino — this is a flavor eigenstate

Let’s make it a muon neutrino from the NuMI beam

A flavor state is in a superposition of mass eigenstates.

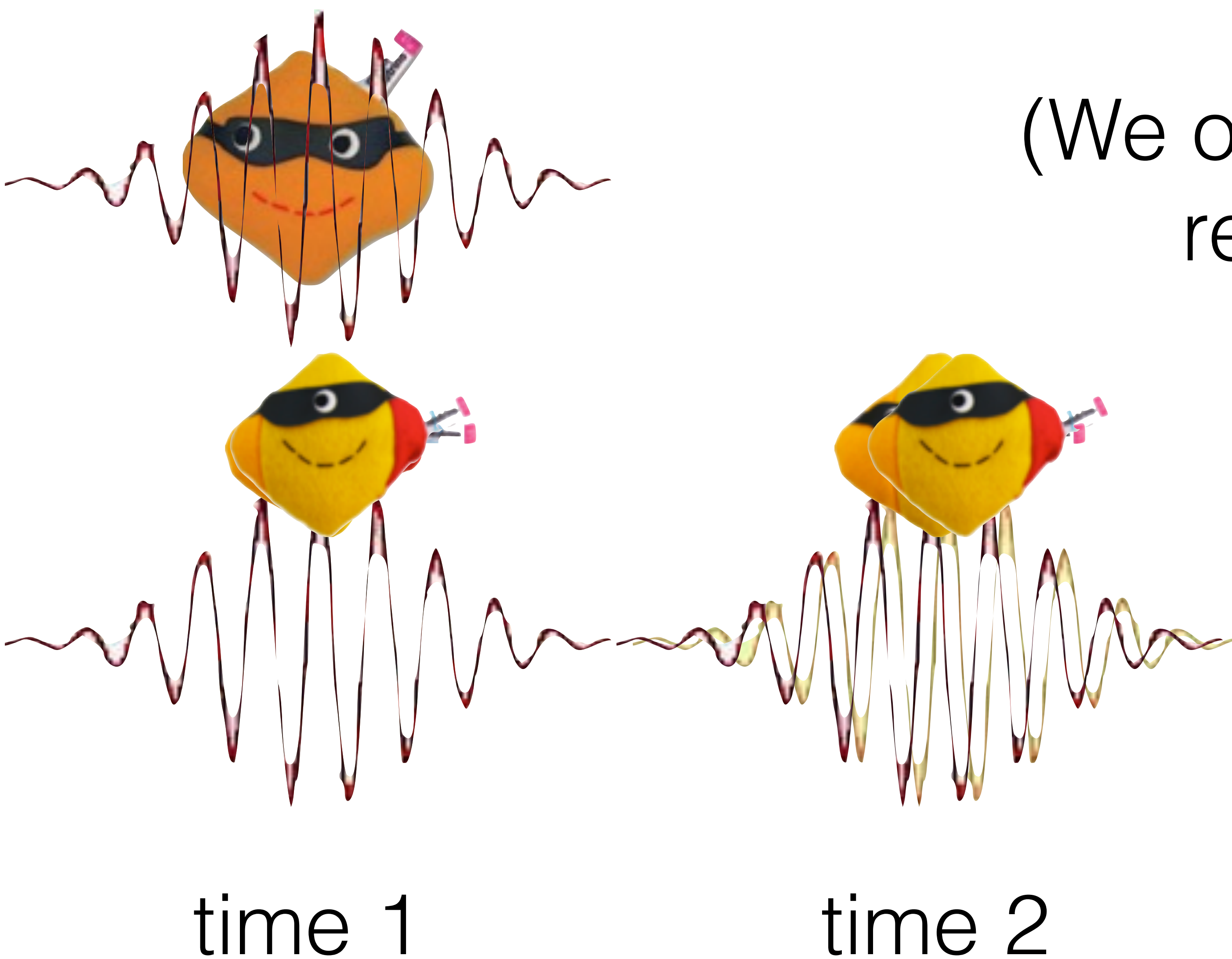


time 1

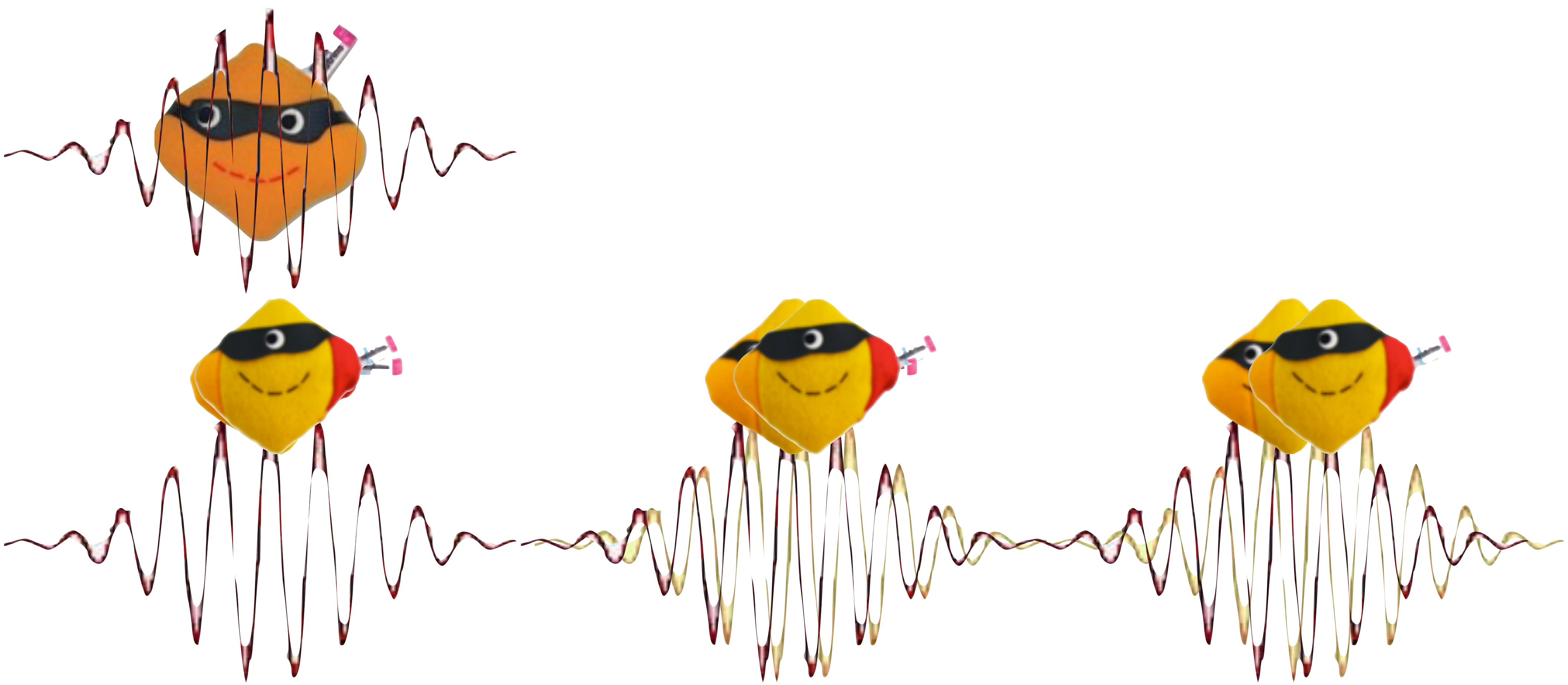
And particles, remember, act as waves — waves can interfere with one another

As the neutrino moves, the mass states composing it begin to fall out of sync

(We only show two here, but in reality there are three)

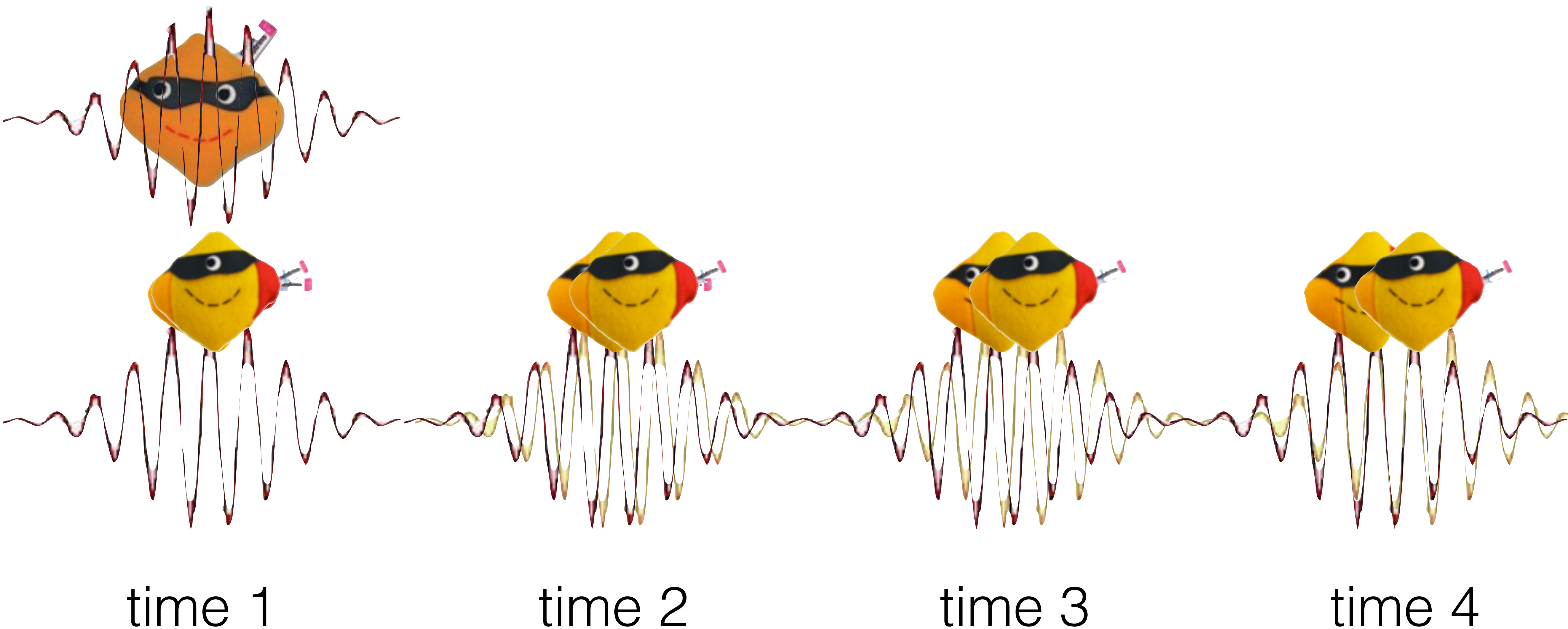


But as the heavier states lag behind, eventually…

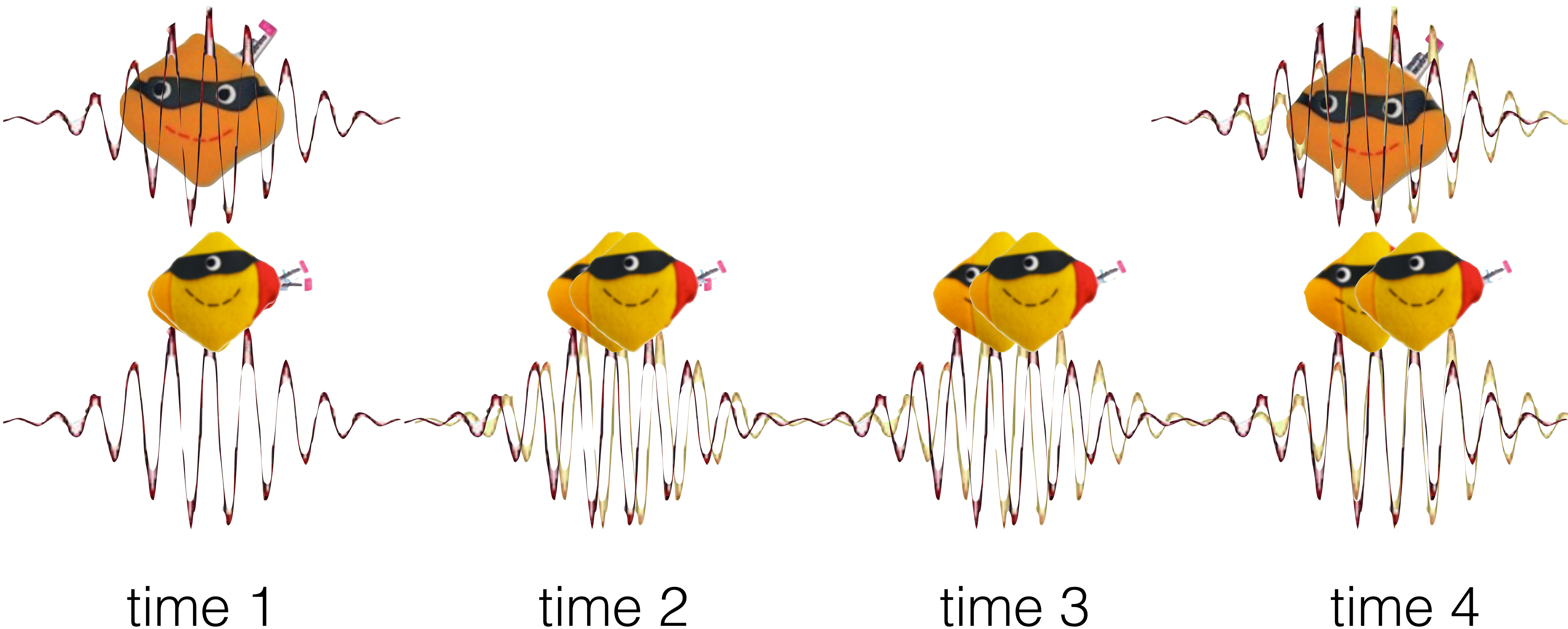


time 1 time 2 time 3

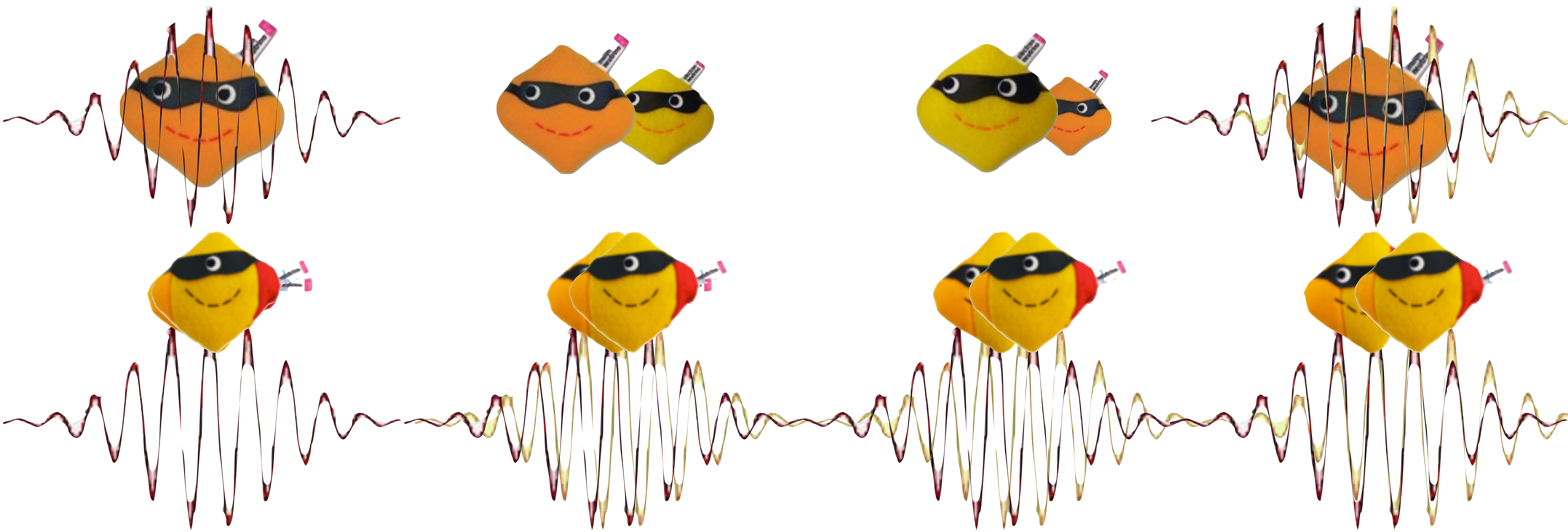
The mass states begin to interfere in a way that looks similar to the way they started



So if the neutrino interacts at time 4, we have a very good chance of observing a muon neutrino again



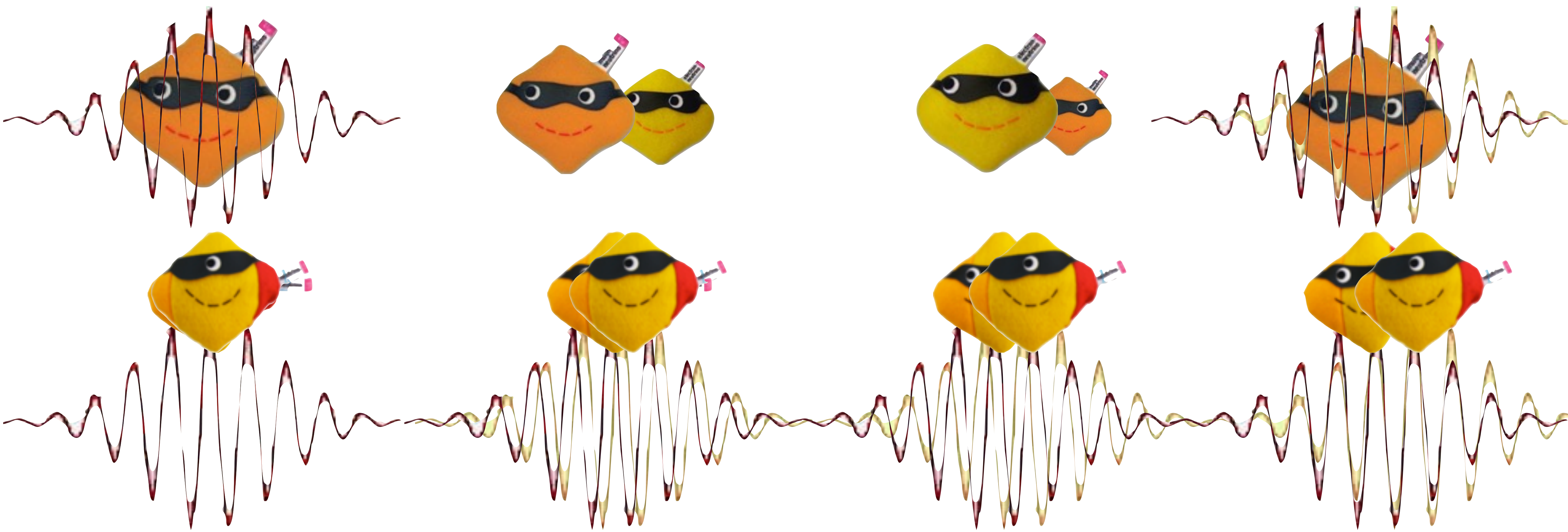
At other times, we might have a better chance of seeing, say, an electron neutrino



time 1 time 2 time 3 time 4

*Don't try to read too much into the wave packets —> plushies translation!
The plushie distributions shown are ~arbitrary.

This is, in essence, neutrino oscillation

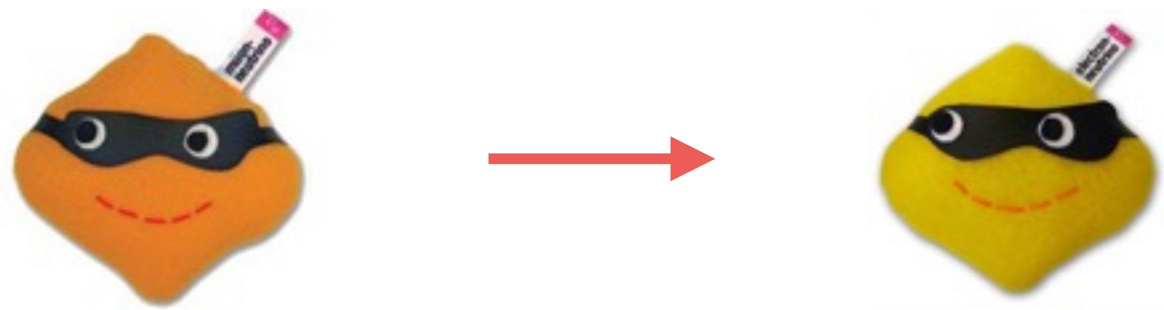


time 1　time 2　time 3　time 4

Again, in reality, there are three mass eigenstates involved!*

*More if there are sterile neutrinos, but we won't talk about them in this talk.

Neutrino oscillation is described by a whole slew of variables



$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= \mid U_{\mu 1}^* e^{-im_1^2 L/2E} U_{e1} + U_{\mu 2}^* e^{-im_2^2 L/2E} U_{e2} + U_{\mu 3}^* e^{-im_3^2 L/2E} U_{e3} \mid^2 \\
&= |2U_{\mu 3}^* U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2U_{\mu 2}^* U_{e2} \sin \Delta_{21}|^2 \\
&\approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2 .
\end{aligned}
$$

Equation Source: S. Parke, "Determining the Neutrino Mass Hierarchy"

These variables usually appear **only in combination**.

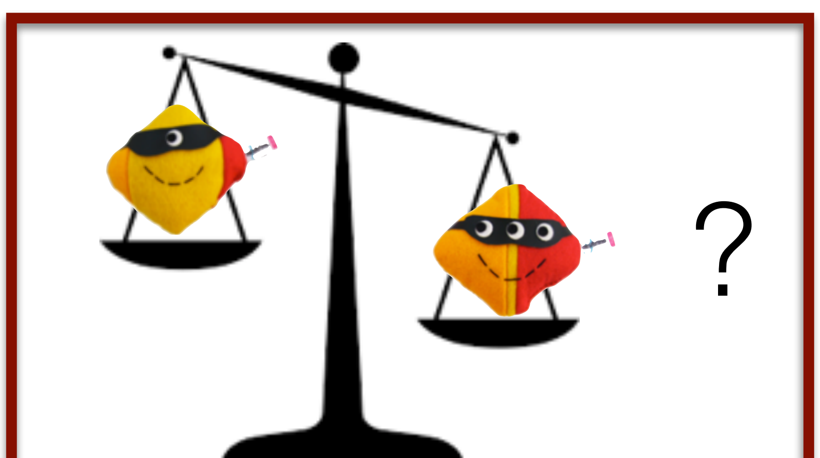
How can we cut these terms apart, and see what nature has to tell us?

Image (without plushies): Fermilab Today

Image: Wikipedia, Wrestling Ring

δ_{CP}

θ_{23}



$\text{sign}(\Delta m_{32})$

Image Source

PART II
Neutrino masses

We know that there are three neutrino mass states



But there's a lot about these states that is unknown.

For one, the jury's still out on whether the third mass eigenstate is more muon or tau-neutrino like

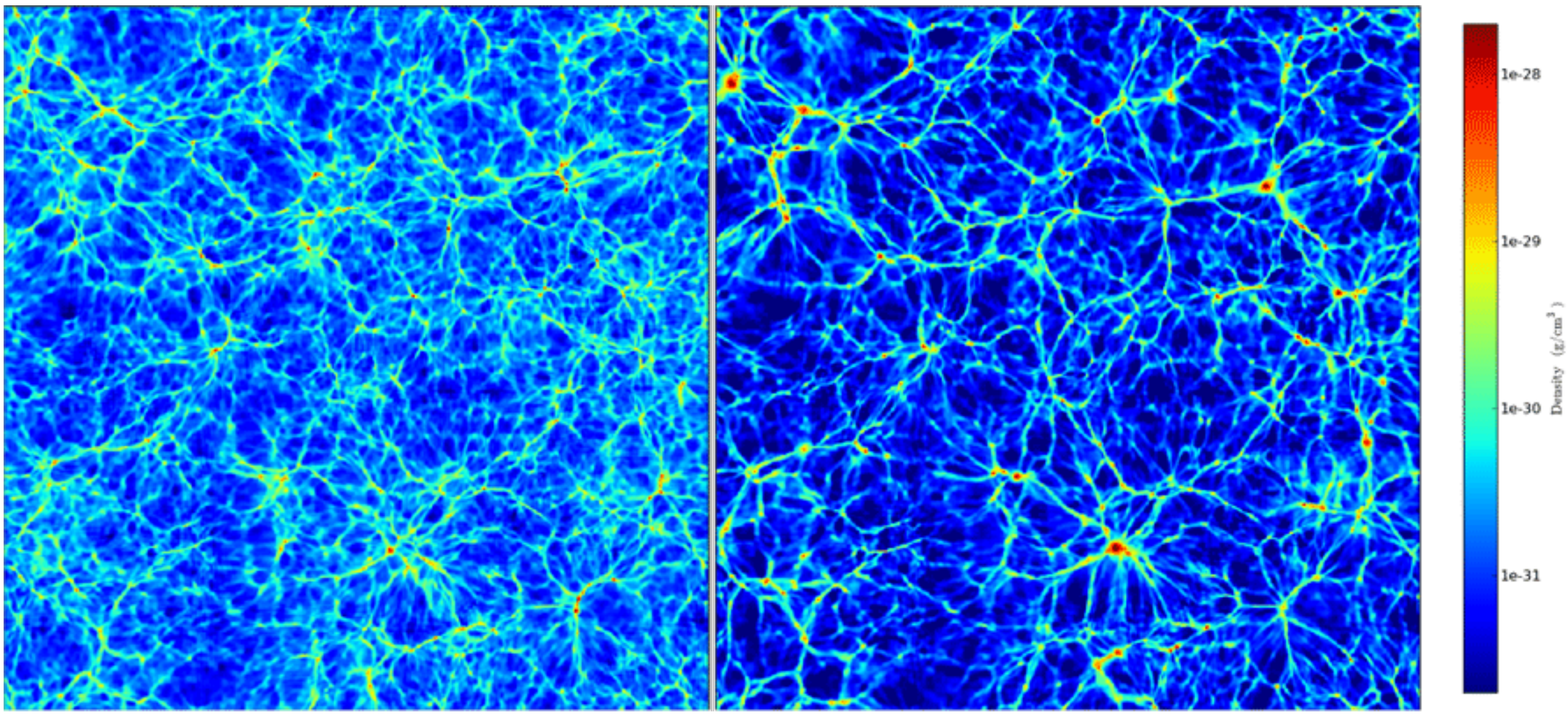
$\theta_{23} > 45^{o}$

$\theta_{23} < 45^{o}$

We also are not even sure what the masses of these states are!

An upper limit on the **sum of the three neutrino masses** is estimated at **< 0.3 eV**

Image: Viewpoint: Galaxies weight in on neutrinos



Massive Neutrinos Massless Neutrinos

This was determined by exploring the effect of neutrino mass on structure formation in the early universe

Neutrino masses are oddly small

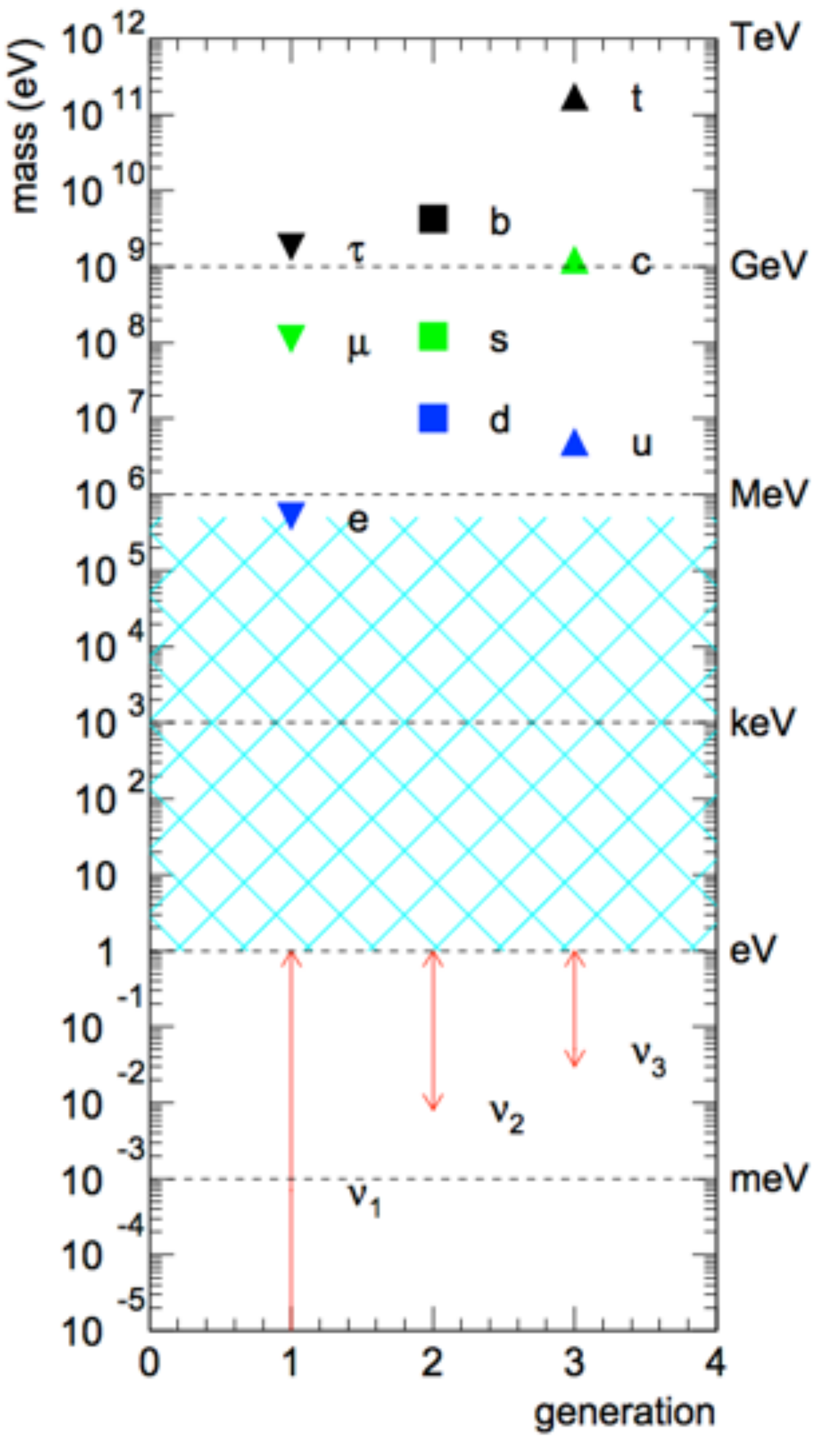


Image: On Determining the Neutrino Mass Hierarchy

The basic Standard Model predicts that they ought to be *massless*.

But neutrinos *have* mass…
six orders of magnitude smaller than the other elementary particles!

Do neutrinos acquire mass in the same way as other particles?

Quarks and charged leptons get their mass from a “Yukawa” coupling to the Higgs field

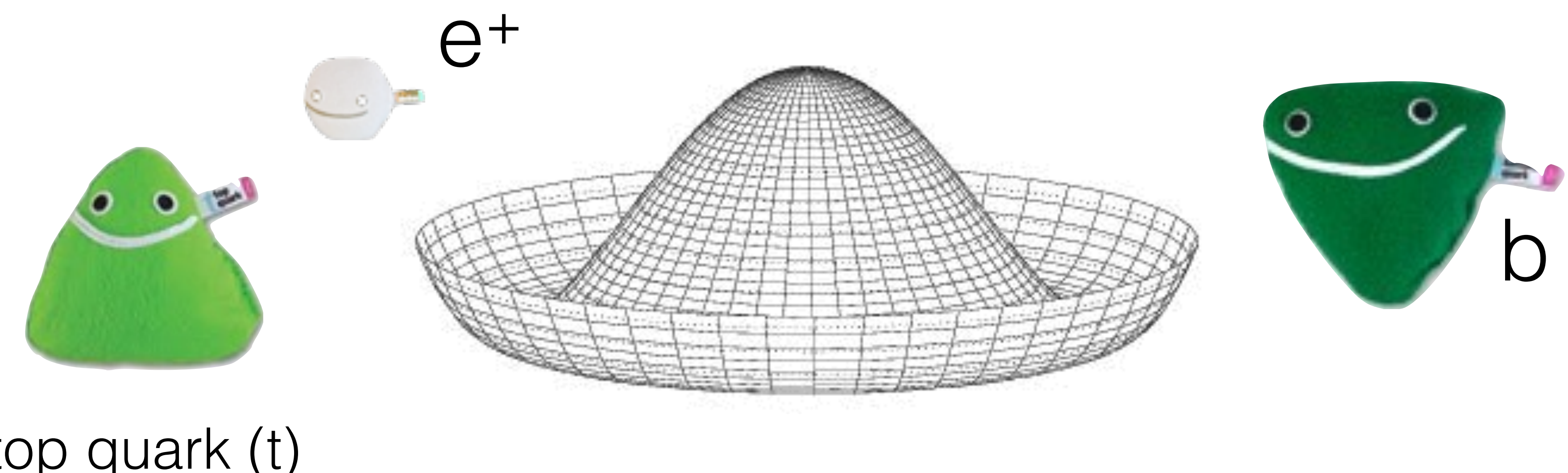
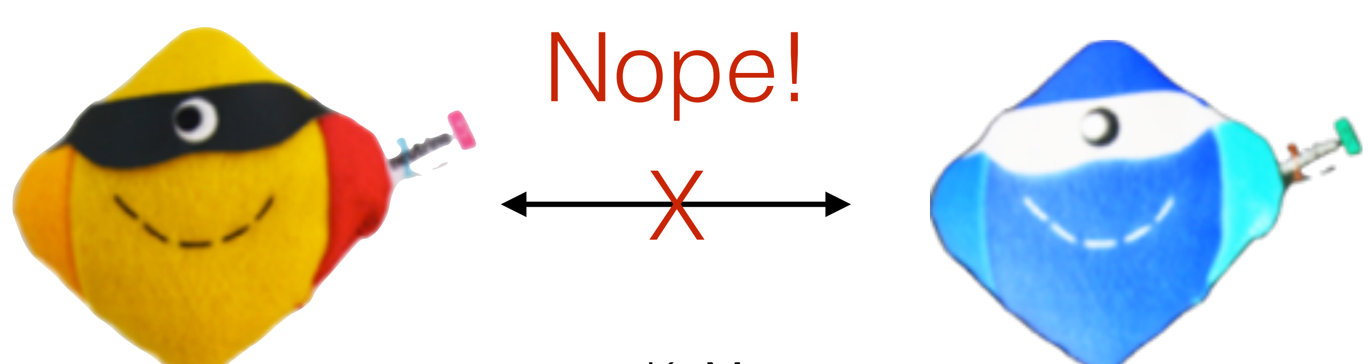


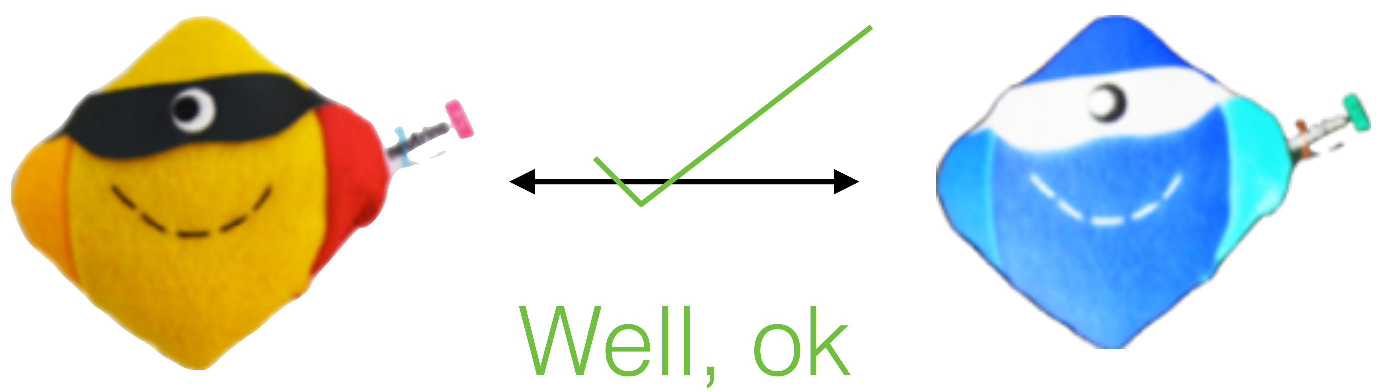
Image: Physics Master Classes

This is called a “Dirac” mass, and has the effect that **Dirac neutrinos and antineutrinos do not “mix”**



There are different mass generators that *do* allow neutrinos and anti-neutrinos to mix.

They **either involve the Higgs field in a different way, or not at all**!

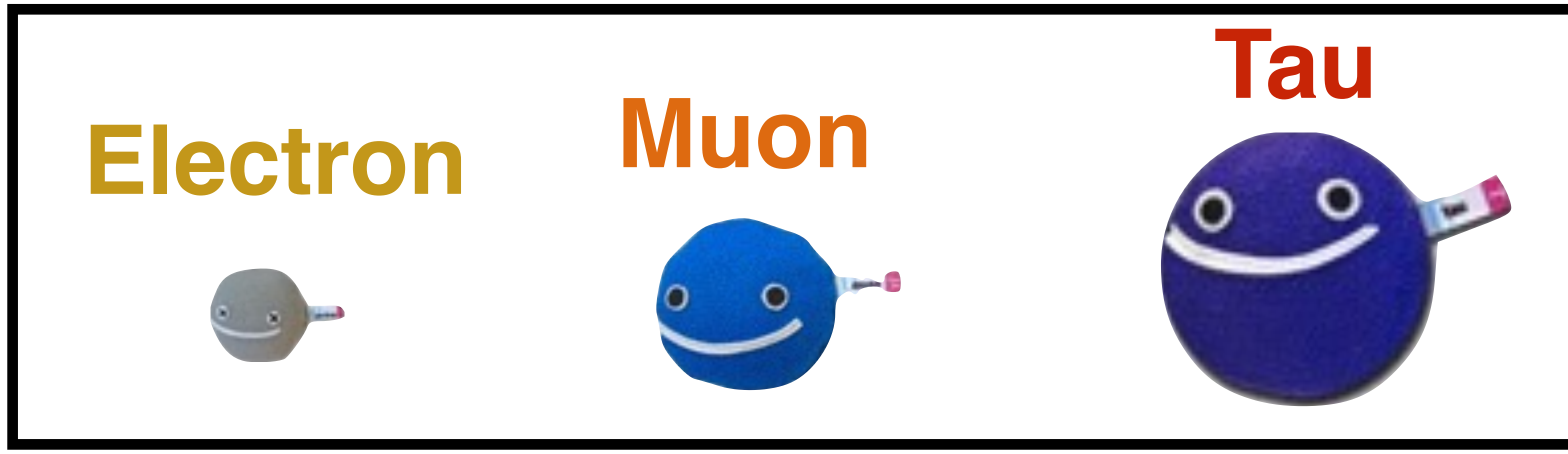


These are called “Majorana” masses, and neutrinos with such masses are **Majorana neutrinos**

A **Majorana neutrino** would be **its own antiparticle**.

Given all of this — do neutrino masses follow expectation?*

The electron is lighter than the muon, is lighter than the tau…



So we might vaguely ‘expect’ that neutrinos follow a similar pattern.

In that case, we anticipate:

Mostly electron-neutrino

~ equal contributions from all flavors

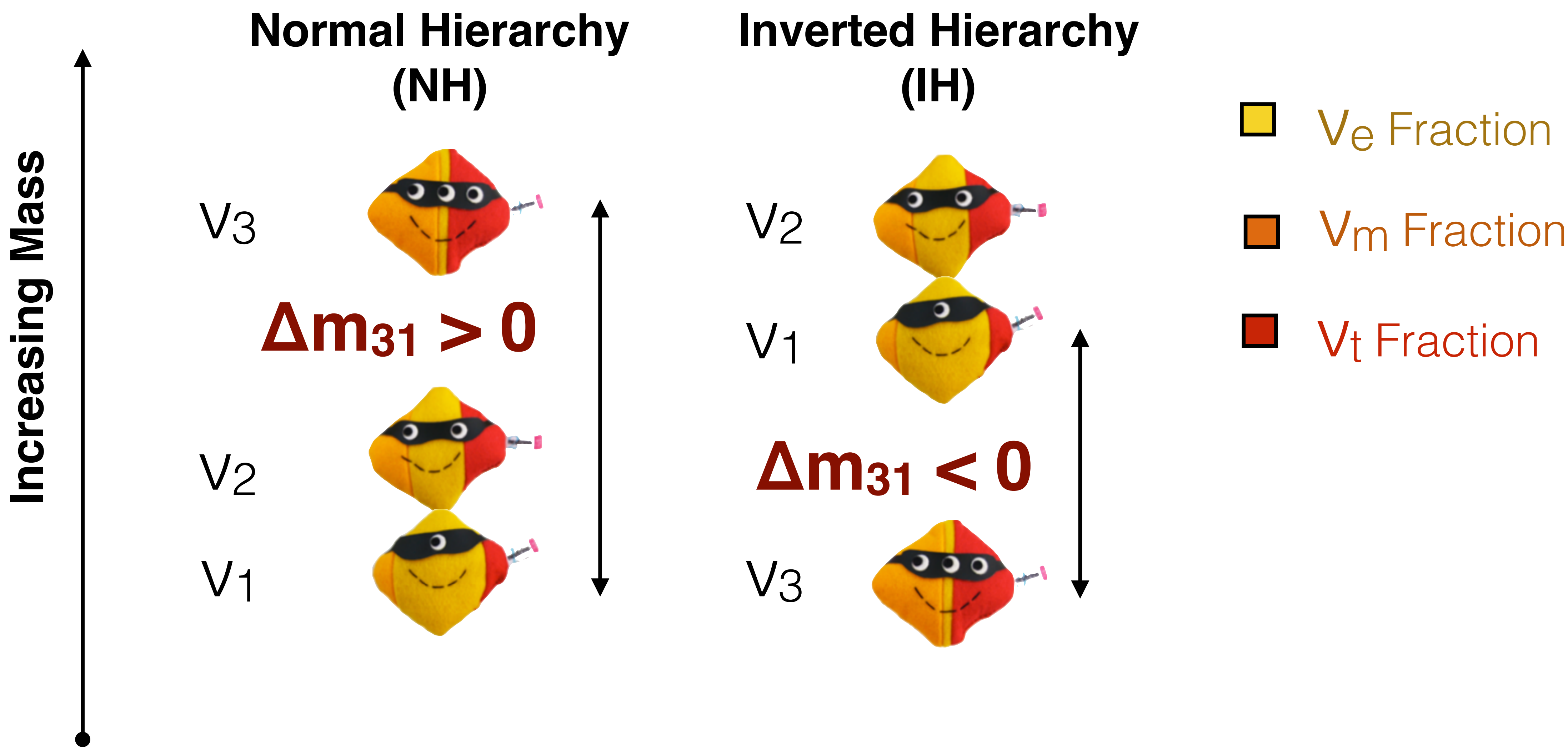
Mostly muon and tau-neutrino

This is the **normal hierarchy**

** The hierarchy does not directly imply Dirac or Majorana neutrinos!*

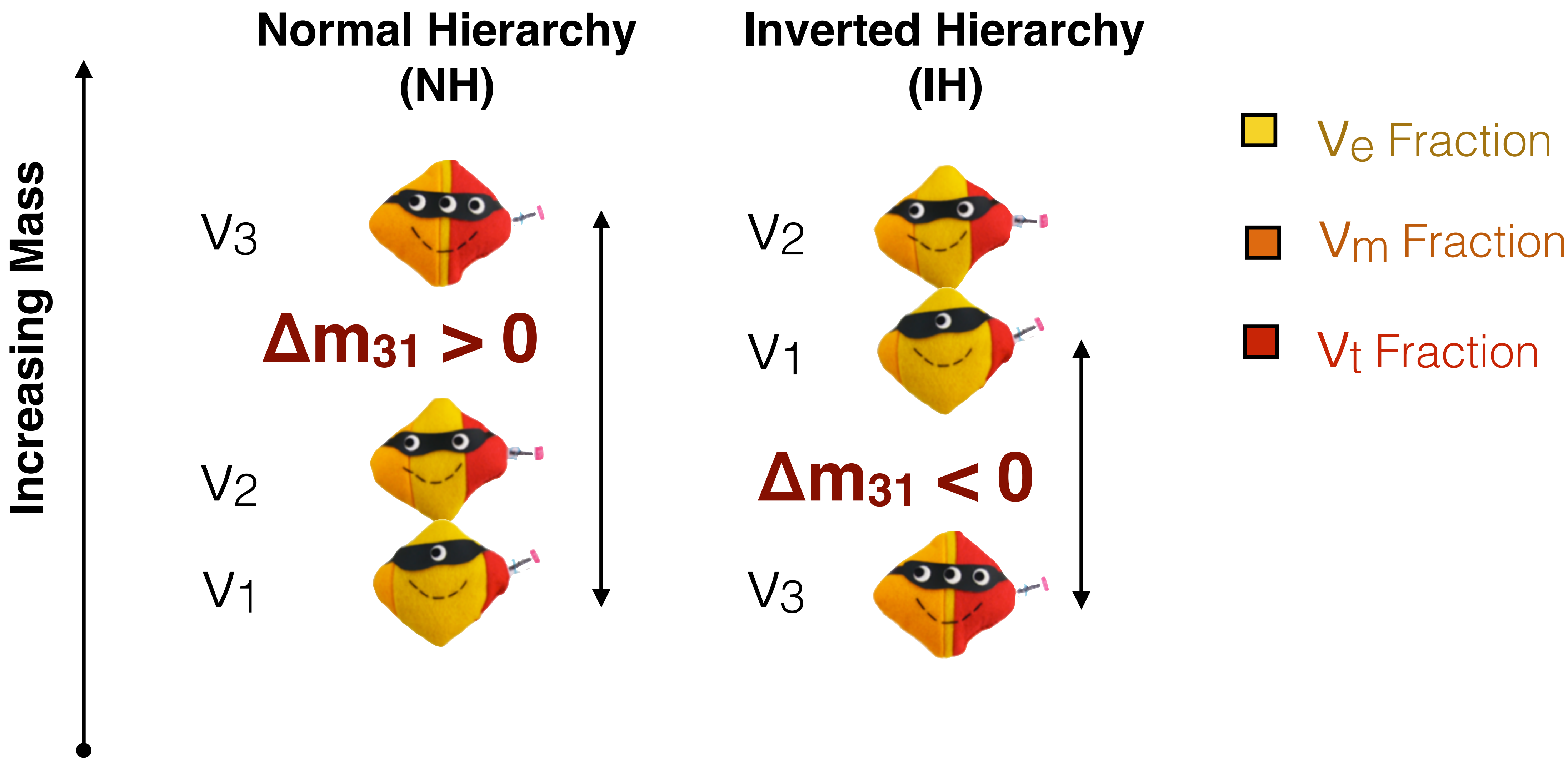
We have not yet determined whether the normal hierarchy holds

We have only determined that $\nu_2 > \nu_1$



If our "expectation" is flipped,
we are looking at the **inverted hierarchy**.

This is the Mass Hierarchy Problem



Solving it would help to untangle our knot.

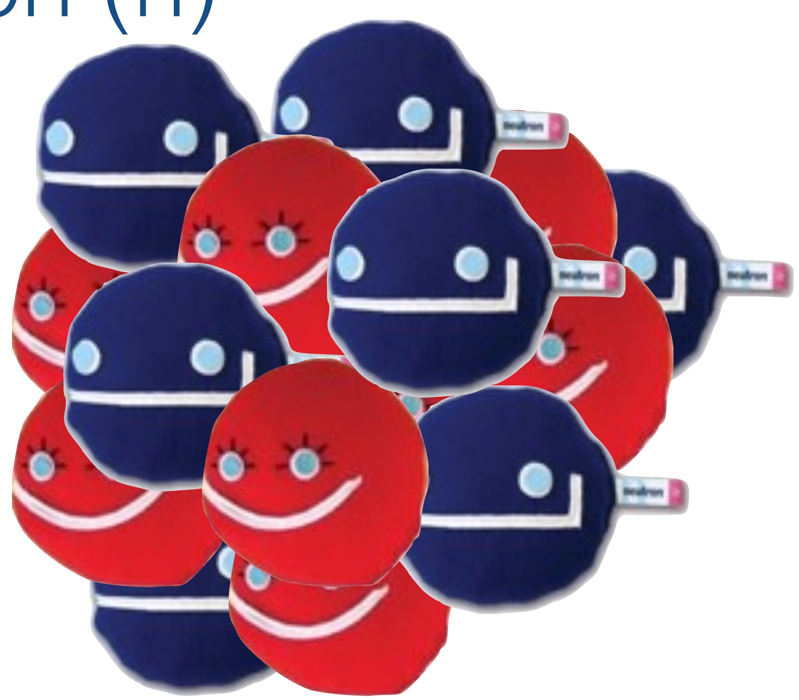
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= |\, U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} \,|^2 \\
&= |2U^*_{\mu 3} U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin \Delta_{21}|^2 \\
&\approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2 .
\end{aligned}
$$

Equation Source: S. Parke, "Determining the Neutrino Mass Hierarchy"

Finding a NH or IH will affect how we answer the Majorana vs Dirac question

This might be done by looking for neutrino-less double-beta decay (0vββ)

neutron (n)



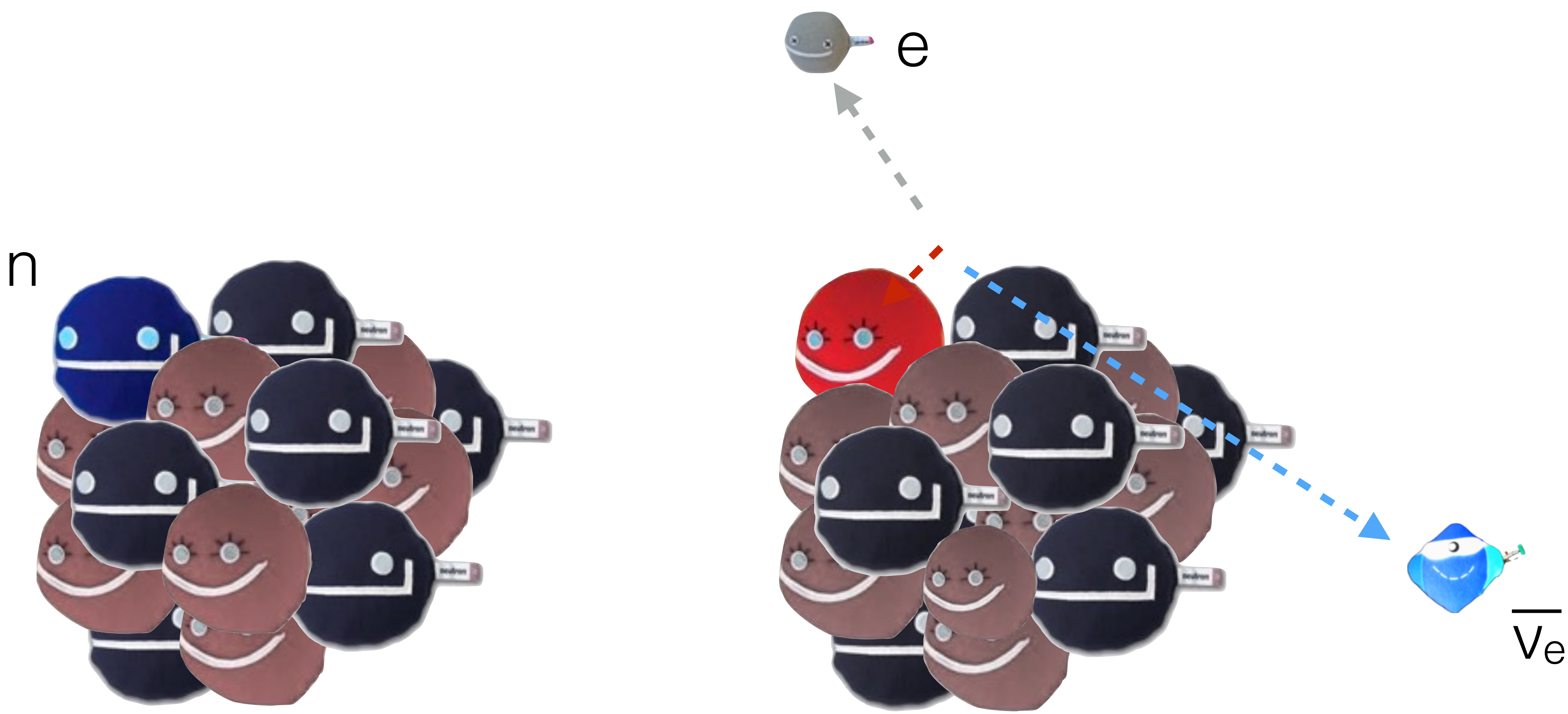
proton (p)

Consider an unstable nucleus at rest.

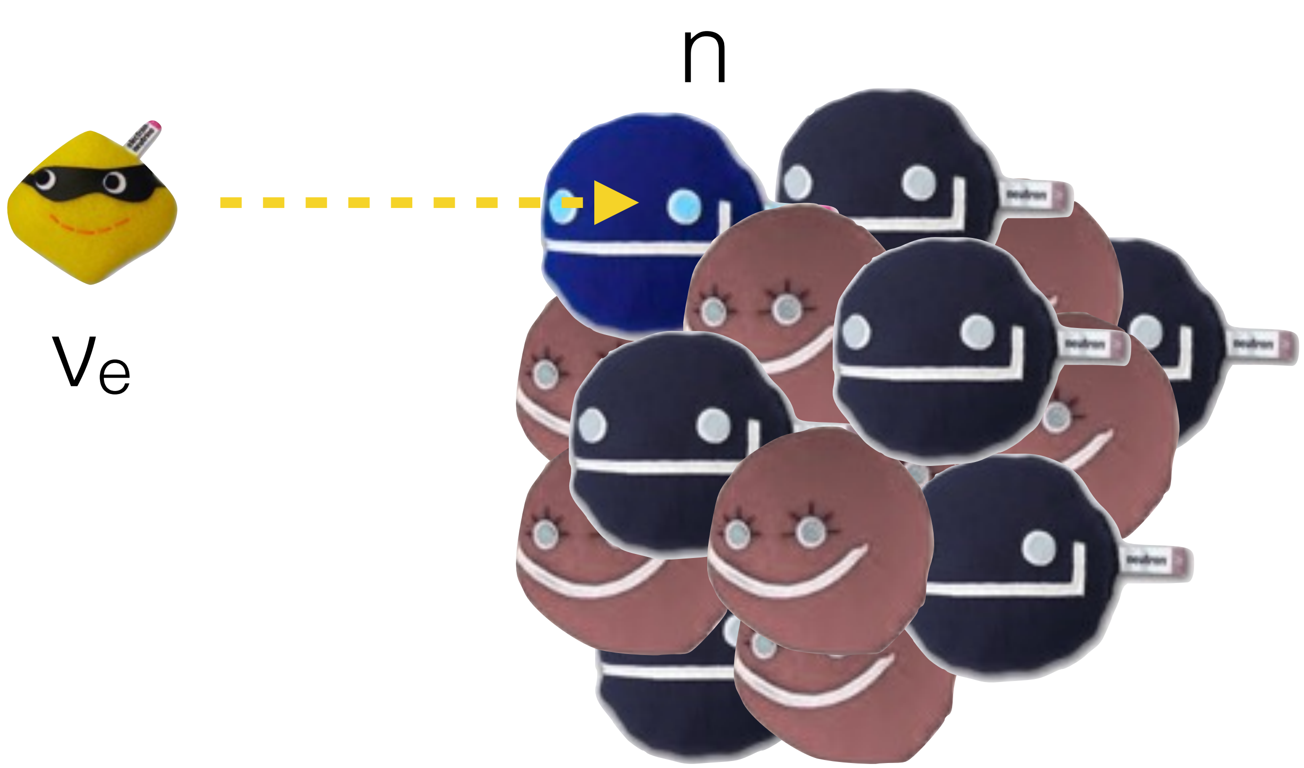
Neutrons can decay…

n

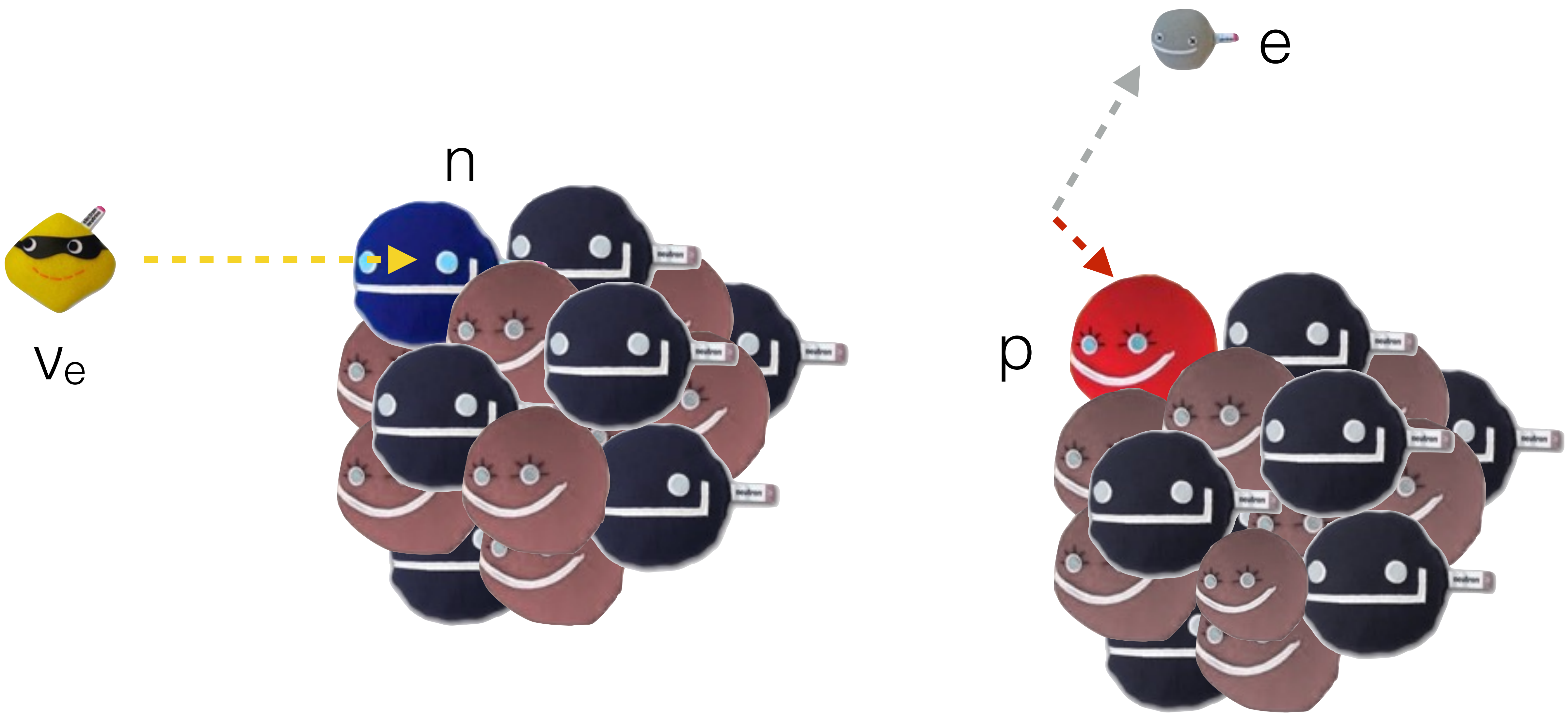
…into protons, with the release of an anti-neutrino and an electron



Also recall that an neutrino can convert a neutron into a proton



Also recall that an neutrino can convert a neutron into a proton

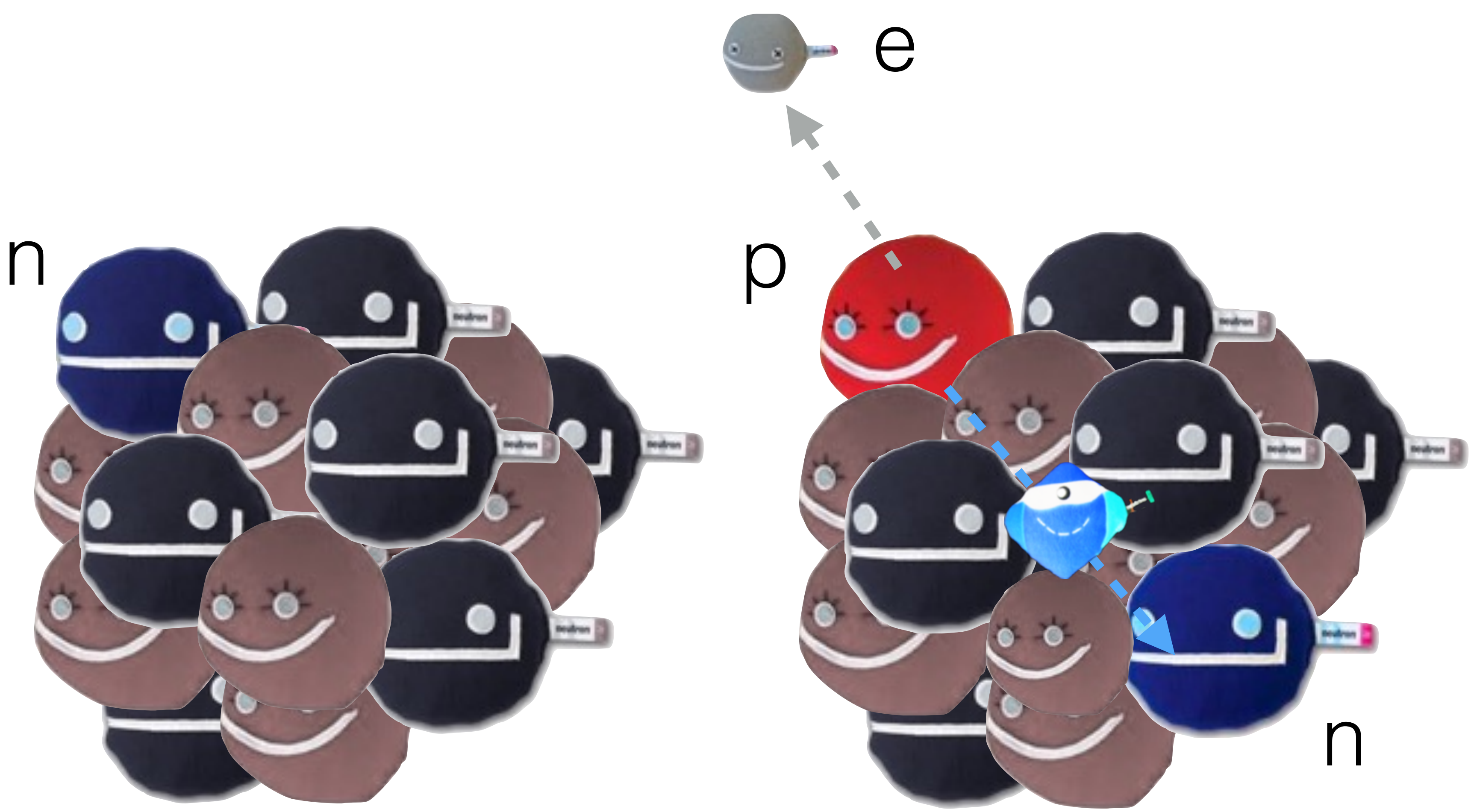


An electron neutrino is ‘flipped’ into an electron in the process

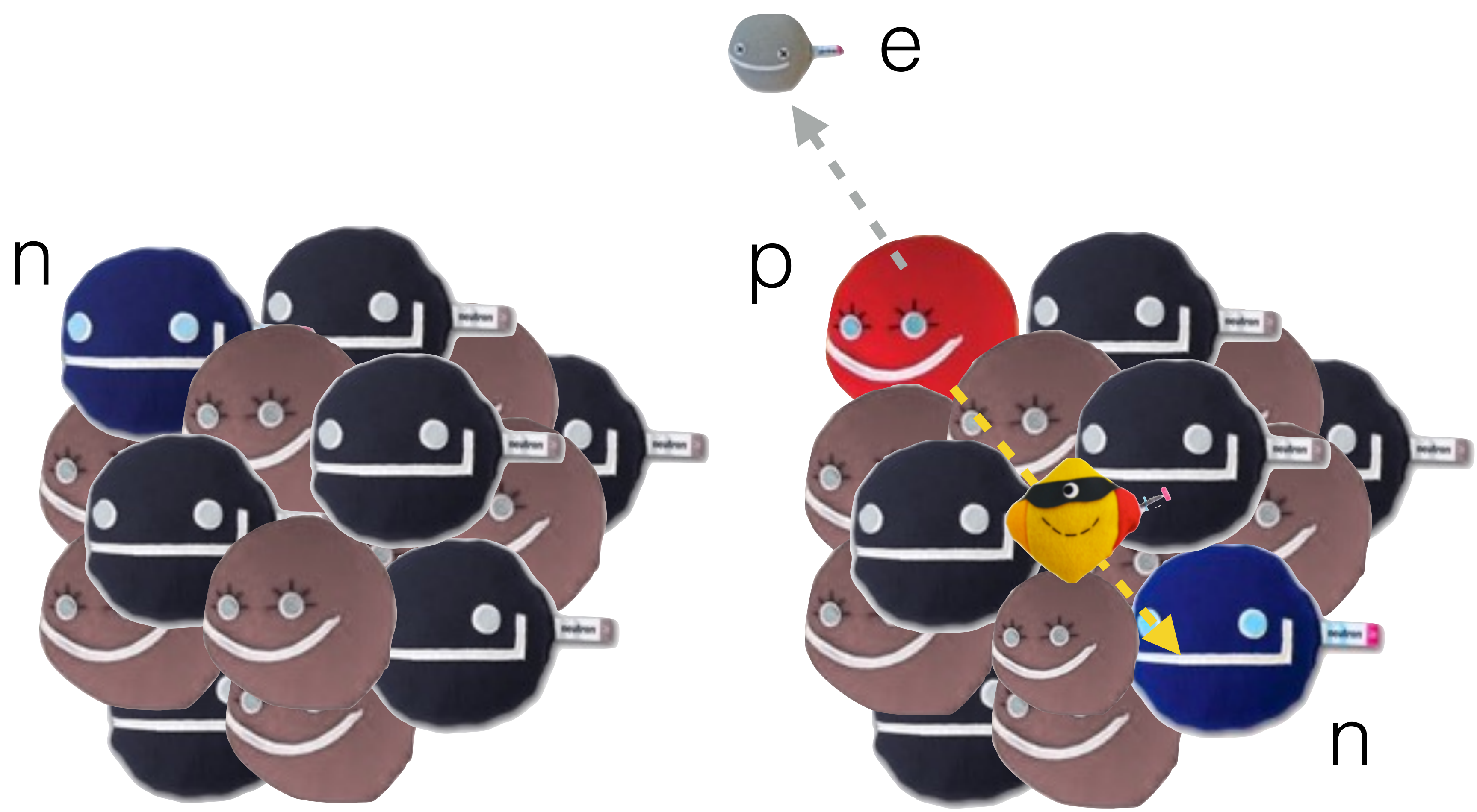
But if a neutrino is its own antineutrino, then we might see…

n

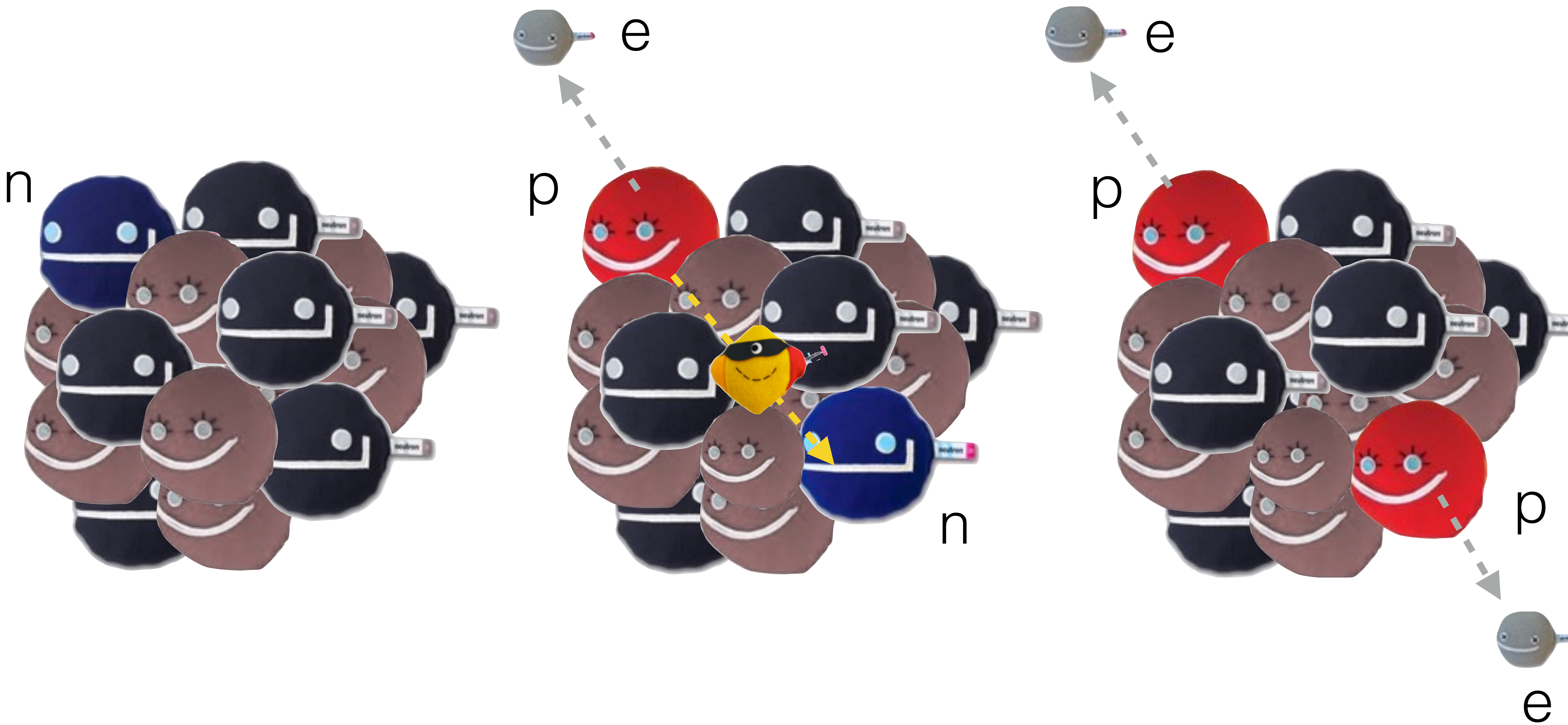
That the **anti-neutrino** produced by neutron decay…



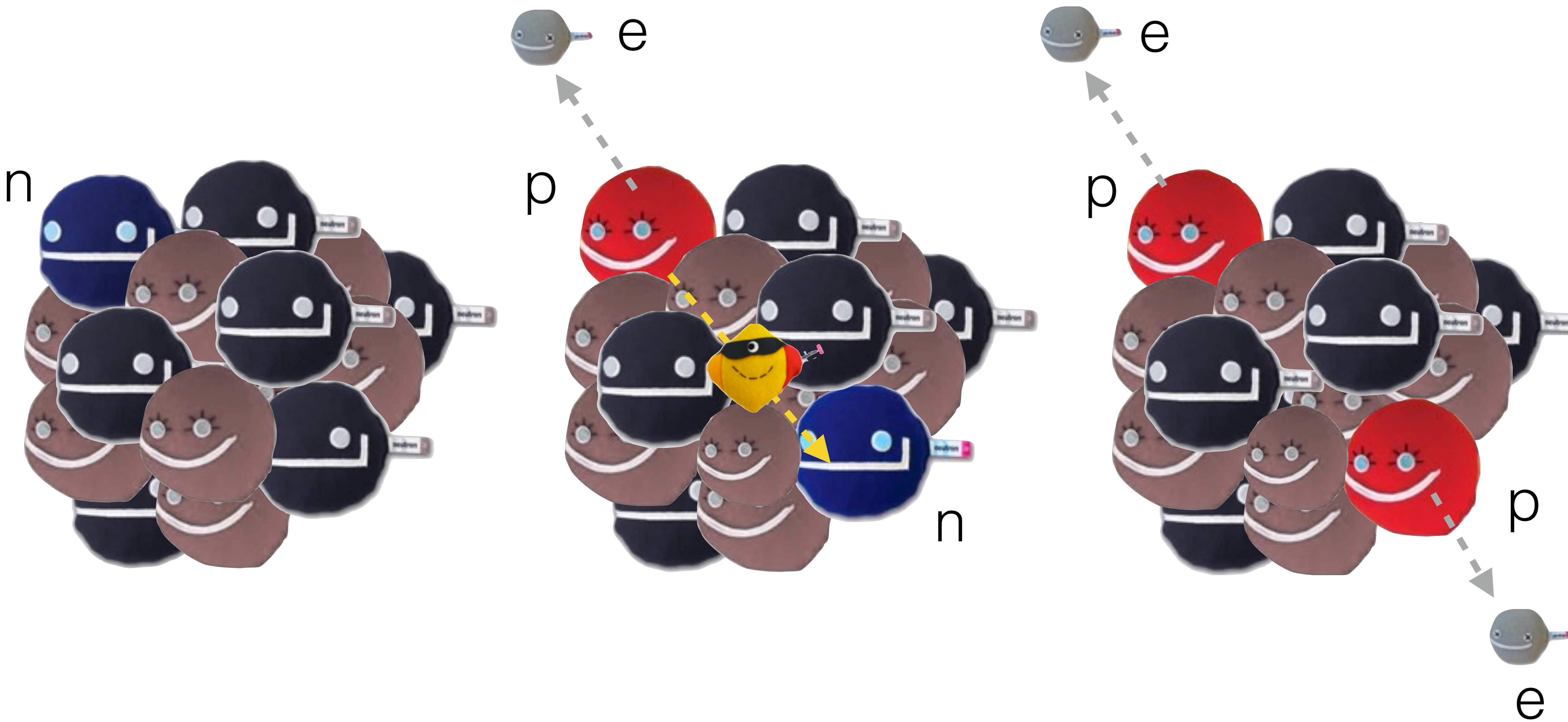
Will interact **as a neutrino** with another neutron in the same nucleus



Producing two beta (electron) particles, but *no neutrinos*…

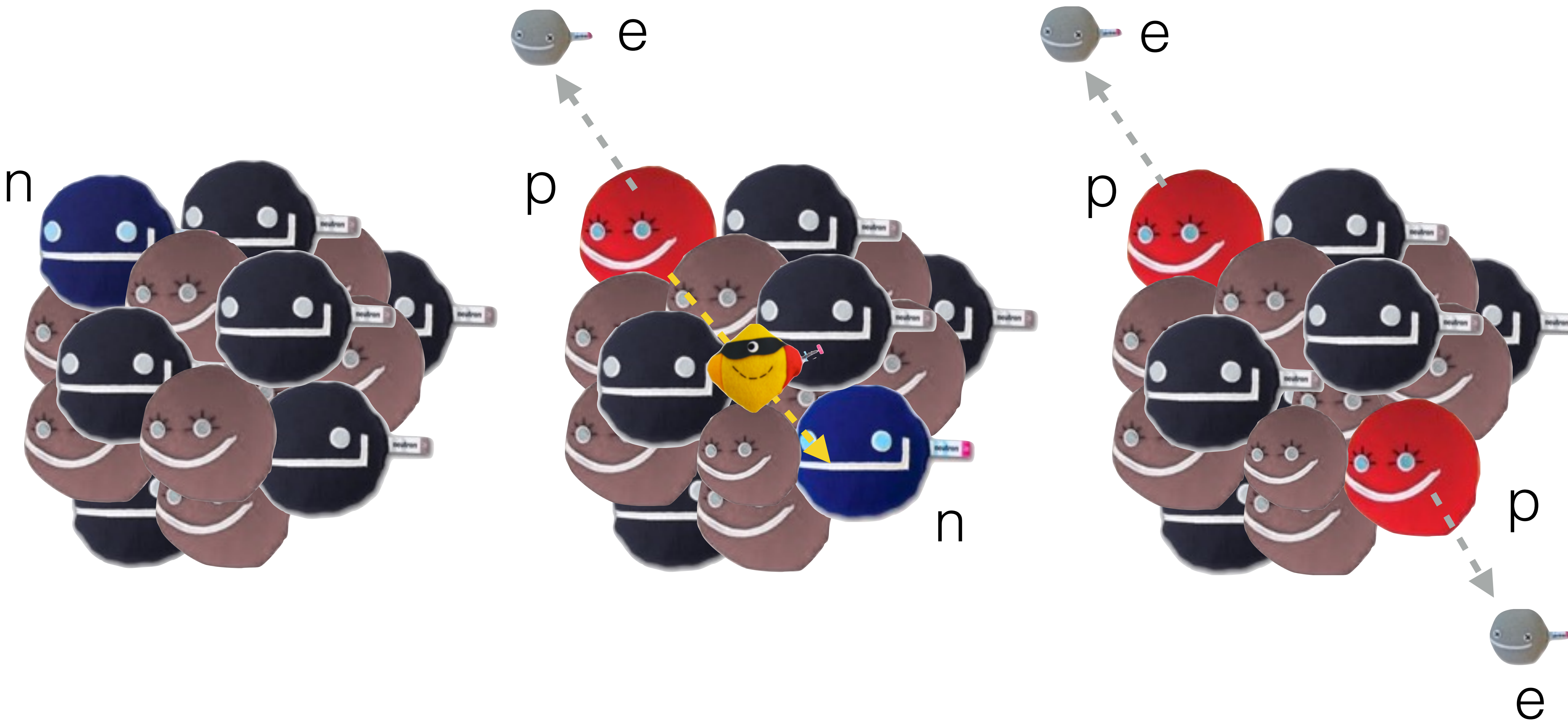


This is called neutrino-less double beta decay (0vββ)



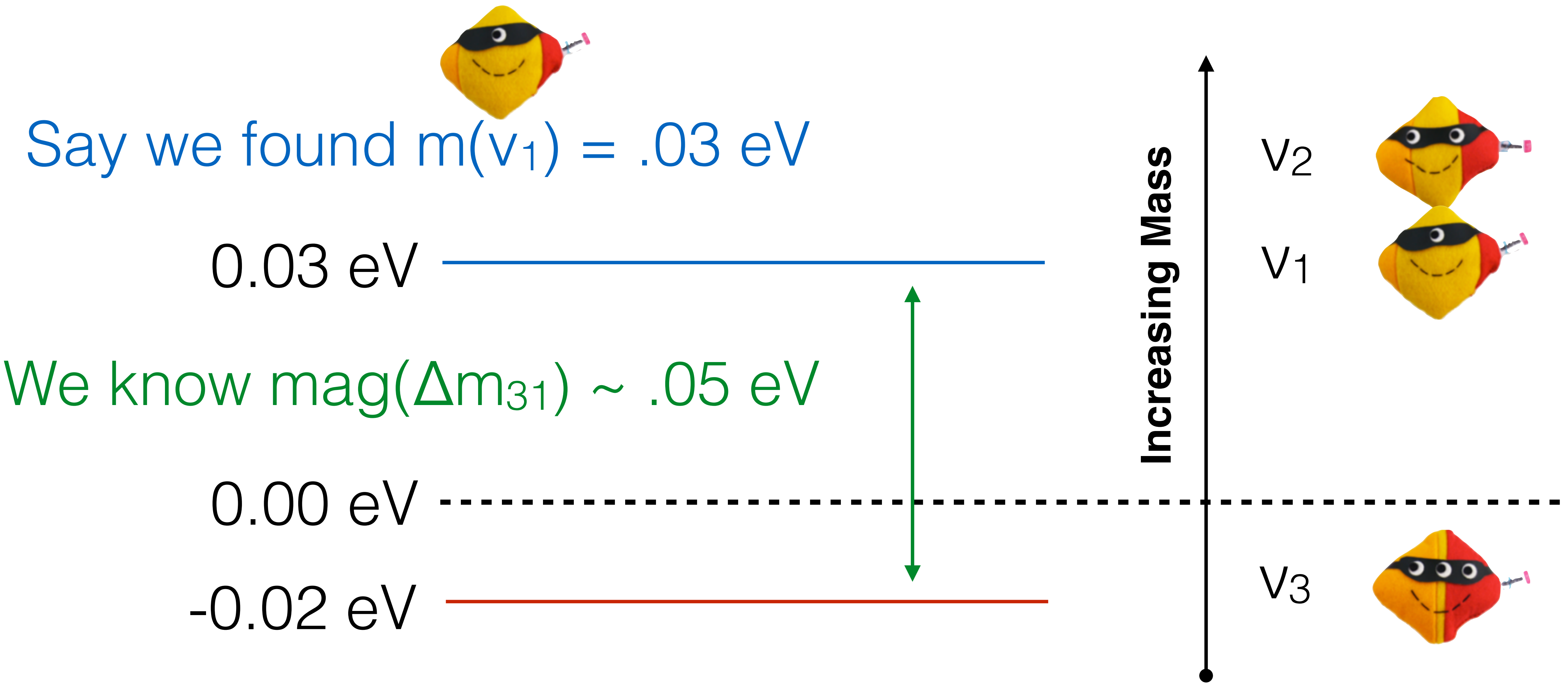
The rate of 0vββ decay is proportional to the value of m_{ee} .

This is called neutrino-less double beta decay ($0\nu\beta\beta$)



The rate of $0\nu\beta\beta$ decay is proportional to the value of m_{ee} .
The value of m_{ee} depends on the mass hierarchy.

A **direct mass measurement** could eliminate the inverted hierarchy option



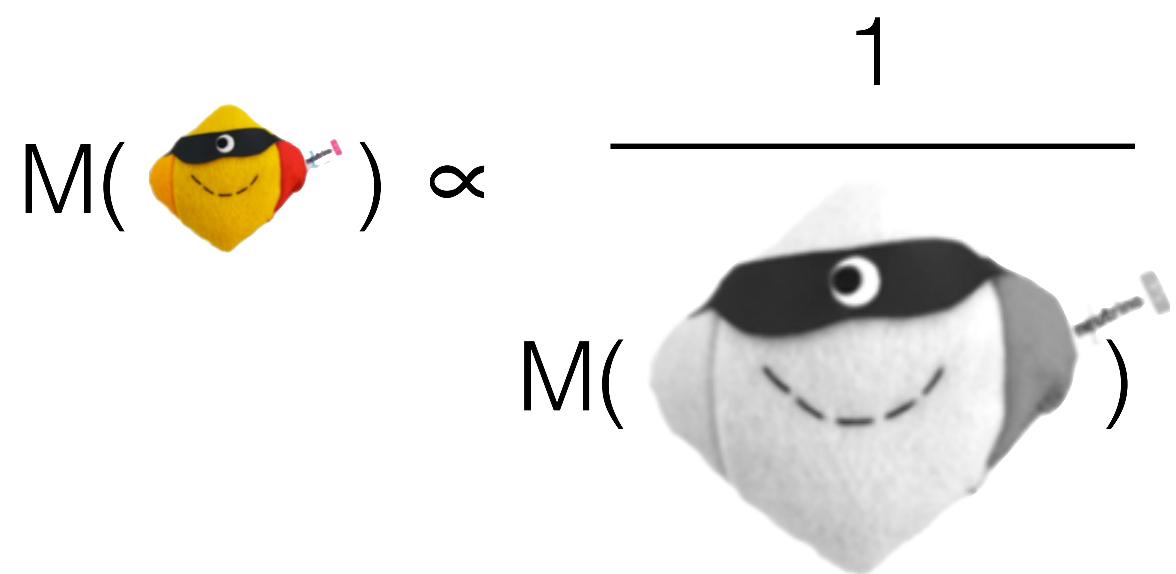
This would put $m(\nu_3) < 0$

And so $m(\nu_1) > m(\Delta m_{31})$
would effectively rule out the **inverted hierarchy**.

What if a neutrino has both a Majorana *and* a Yukawa mass term?

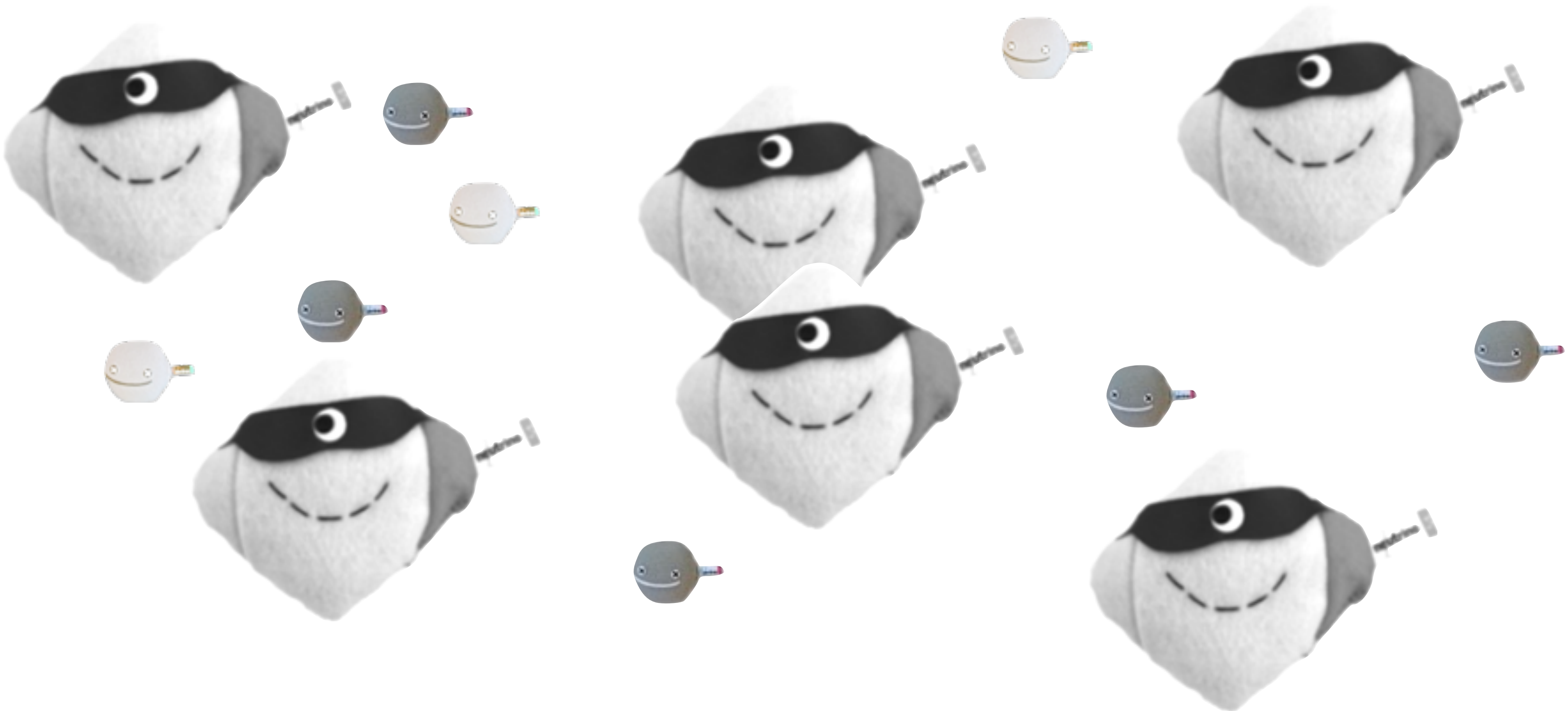
This leads to neutrinos with two distinct masses; if one is very large, the other must be very small.

Image (without plushies): Fermilab Today



This is called the See-Saw mechanism. It predicts that the light neutrinos we see have heavy counterparts.

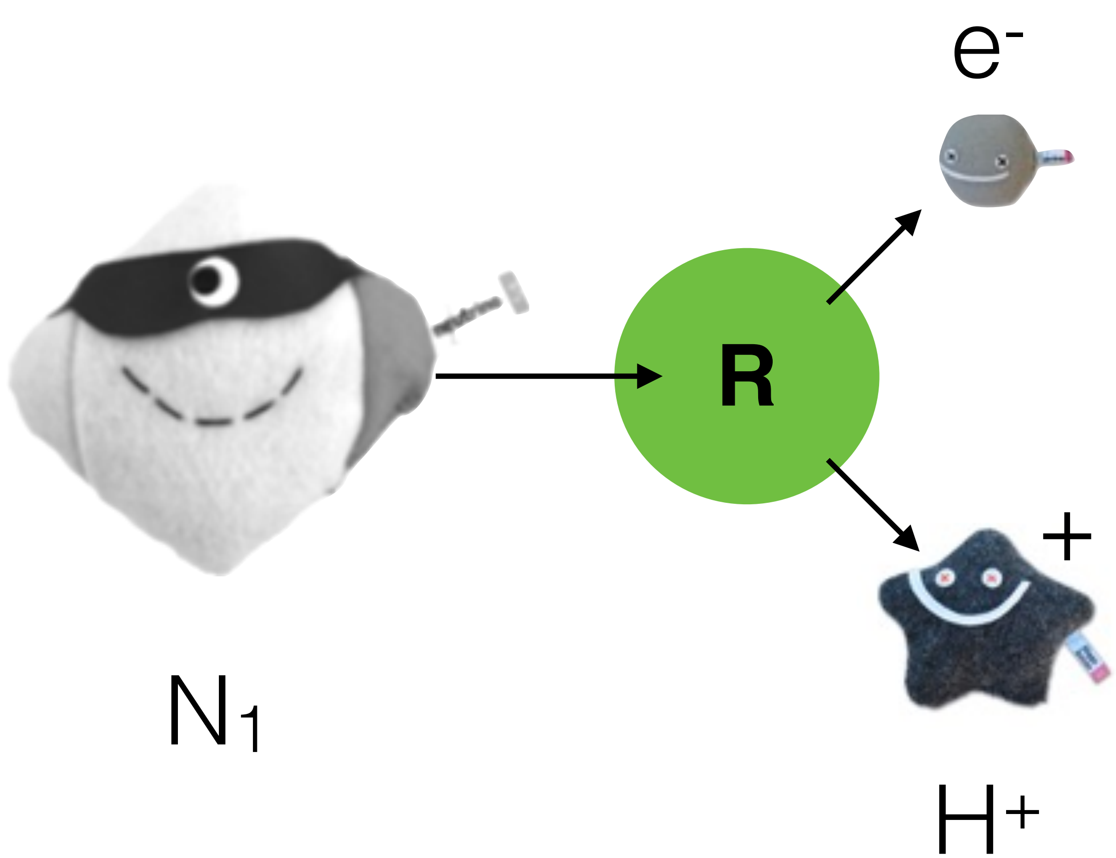
In the early universe, matter and antimatter were produced in equal abundance



This included many heavy neutrinos

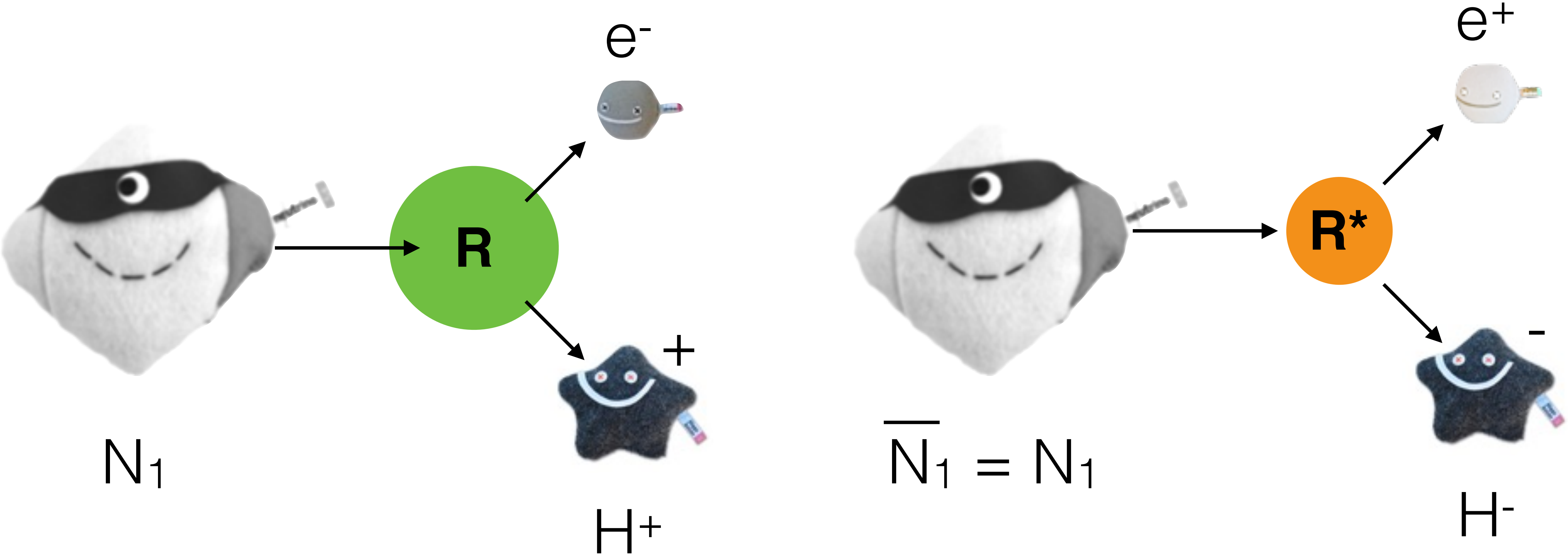
But the neutrino sector includes a CP violating mechanism

In interactions / decays, CP violation allows matter…



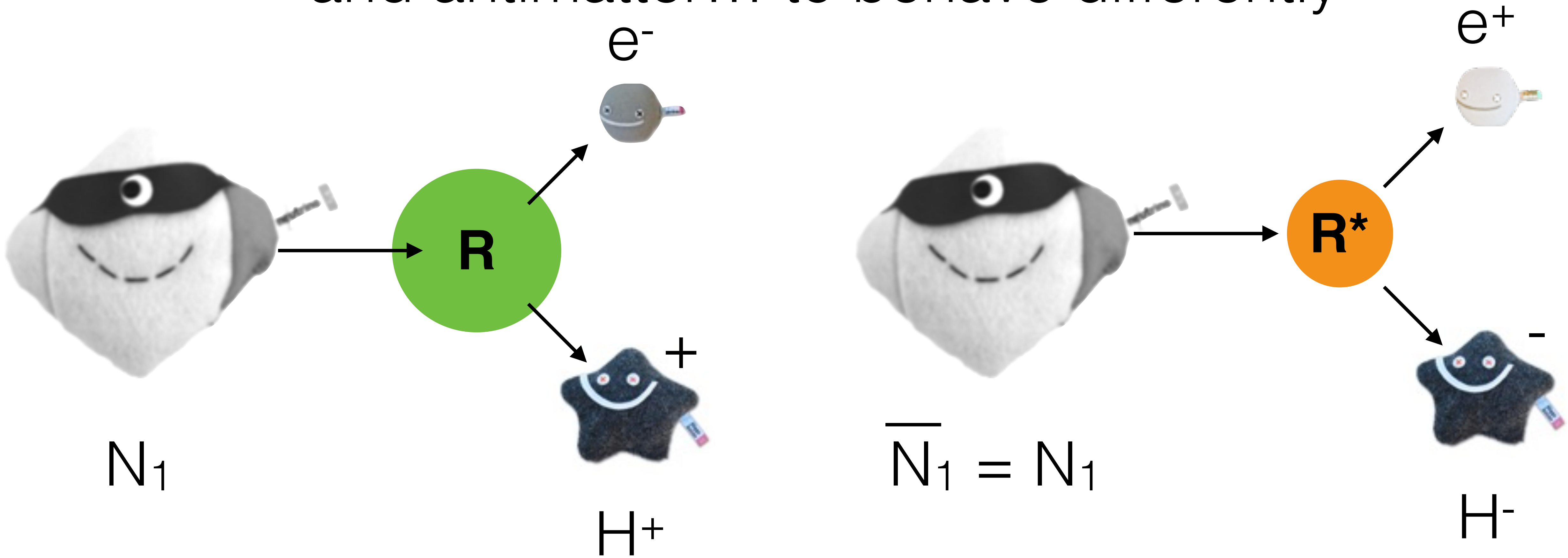
But the neutrino sector includes a CP violating mechanism

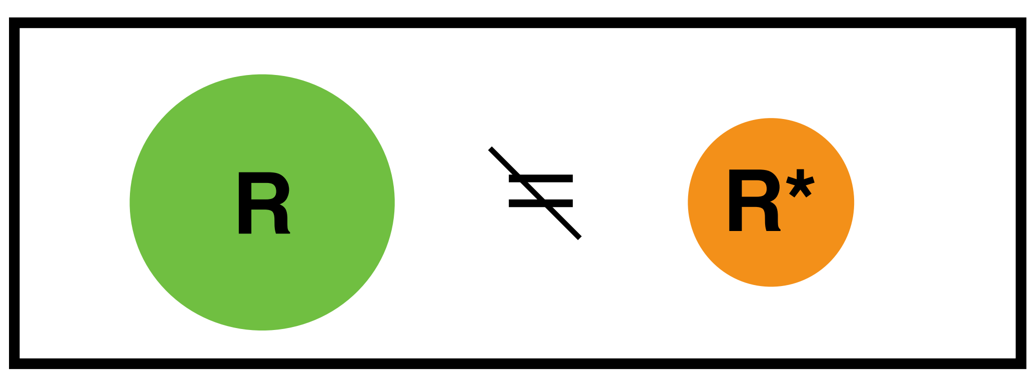
In interactions / decays, CP violation allows matter…
and antimatter…



But the neutrino sector includes a CP violating mechanism

In interactions / decays, CP violation allows matter… and antimatter… to behave differently

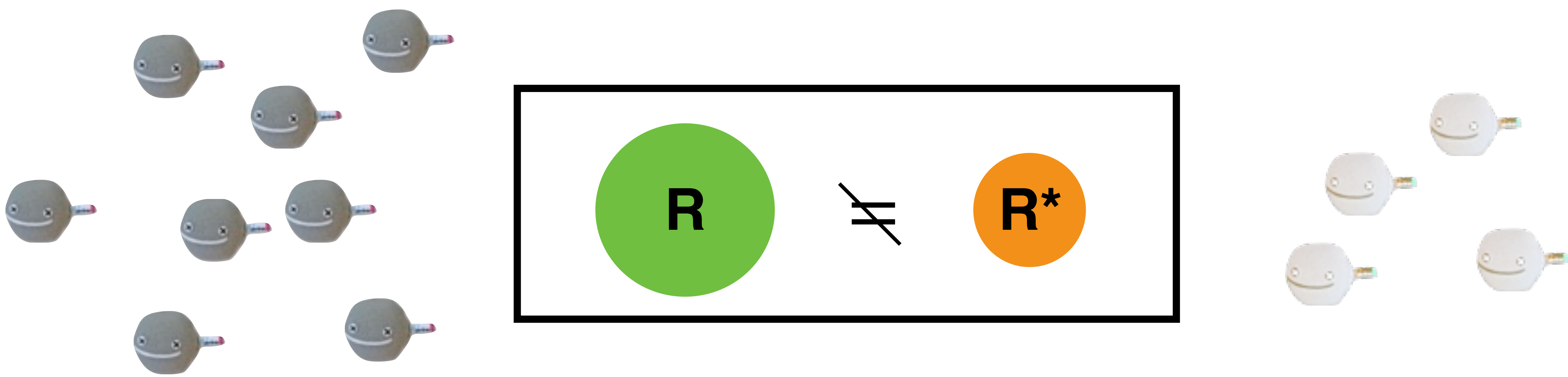




This imbalance in the production of leptons and anti-leptons is called **Leptogenesis**

flock of e^-

coven of e^+

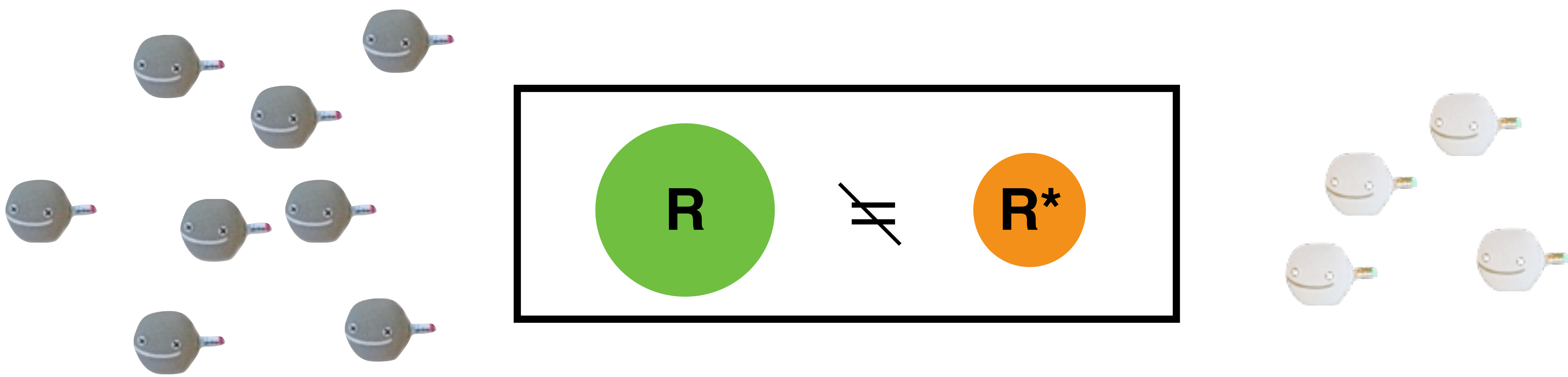


And it could explain why the universe has an excess of matter over antimatter

This imbalance in the production of leptons and anti-leptons is called **Leptogenesis**

flock of e^-

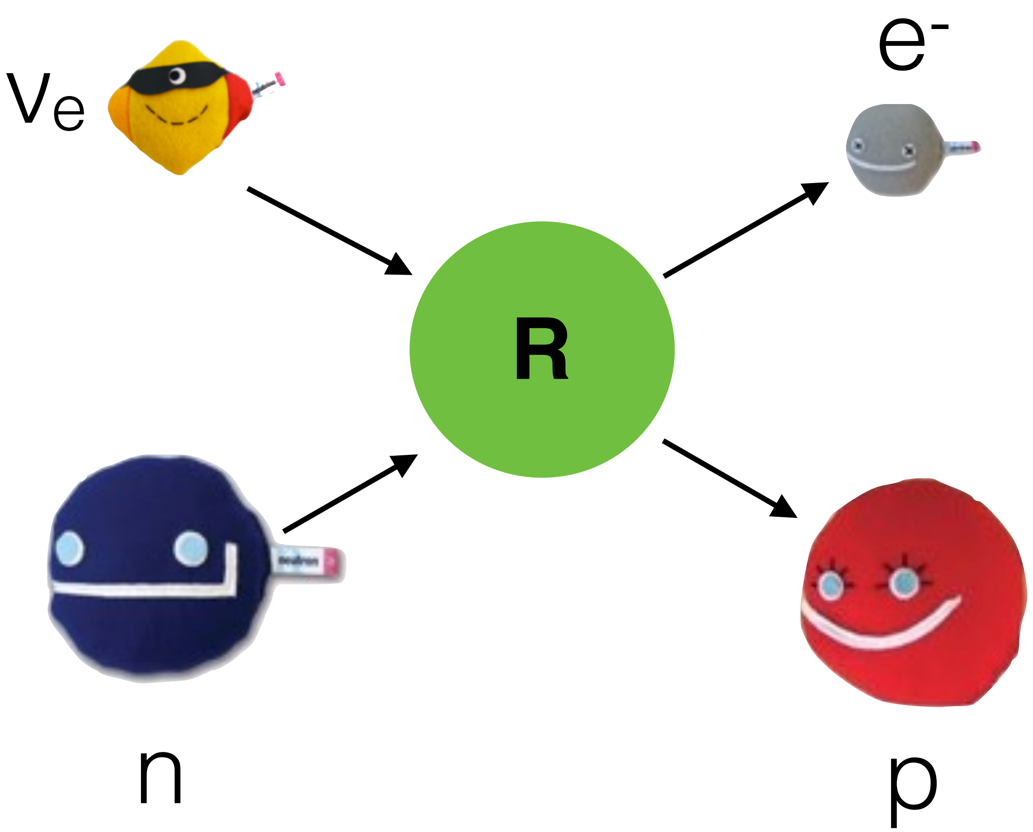
coven of e^+



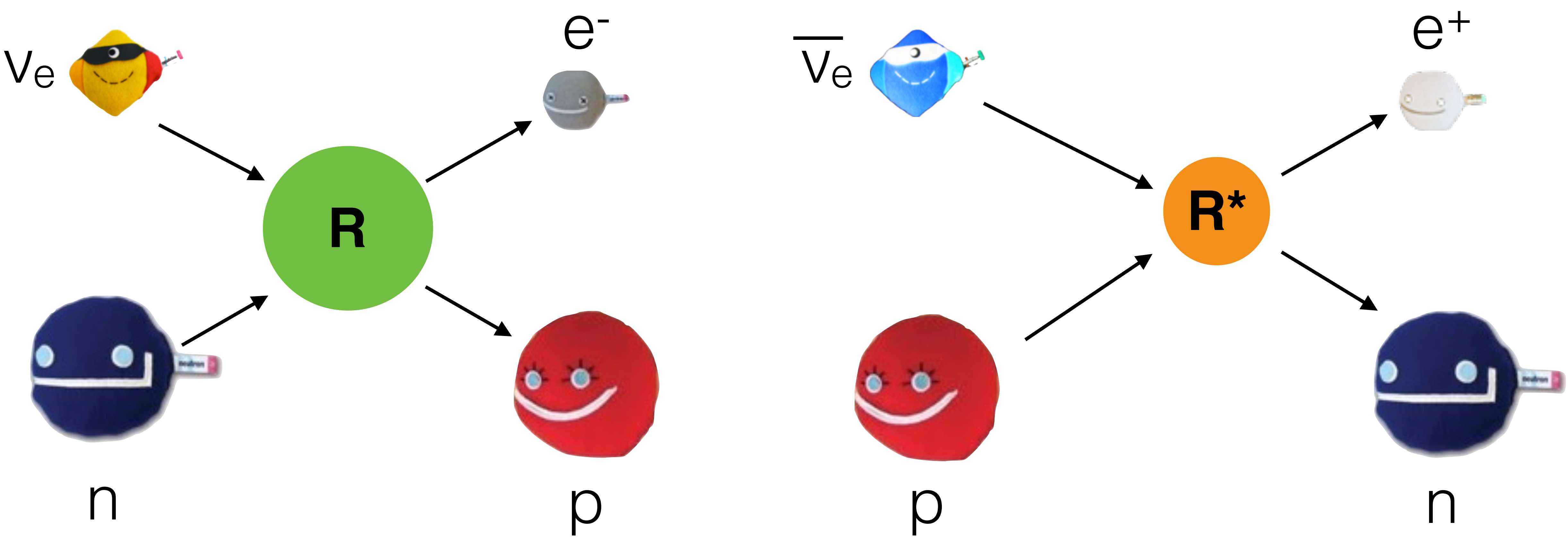
And it could explain why the universe has an excess of matter over antimatter

The **sphaleron** process allows part of this **lepton-antilepton asymmetry** to be converted to a **quark-antiquark asymmetry**

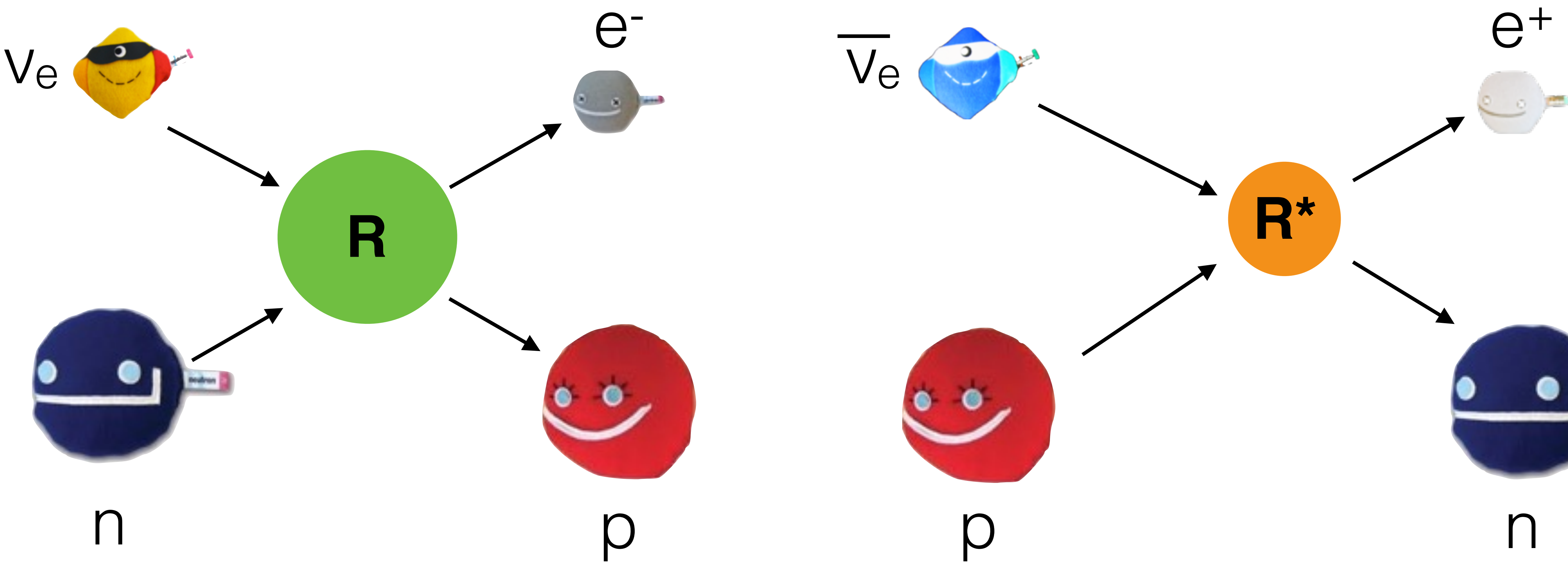
The $\boldsymbol{\delta_{CP}}$ term in neutrino mixing measures **CP violation** in neutrino interactions.



The δ_{CP} term in neutrino mixing measures **CP violation** in neutrino interactions.

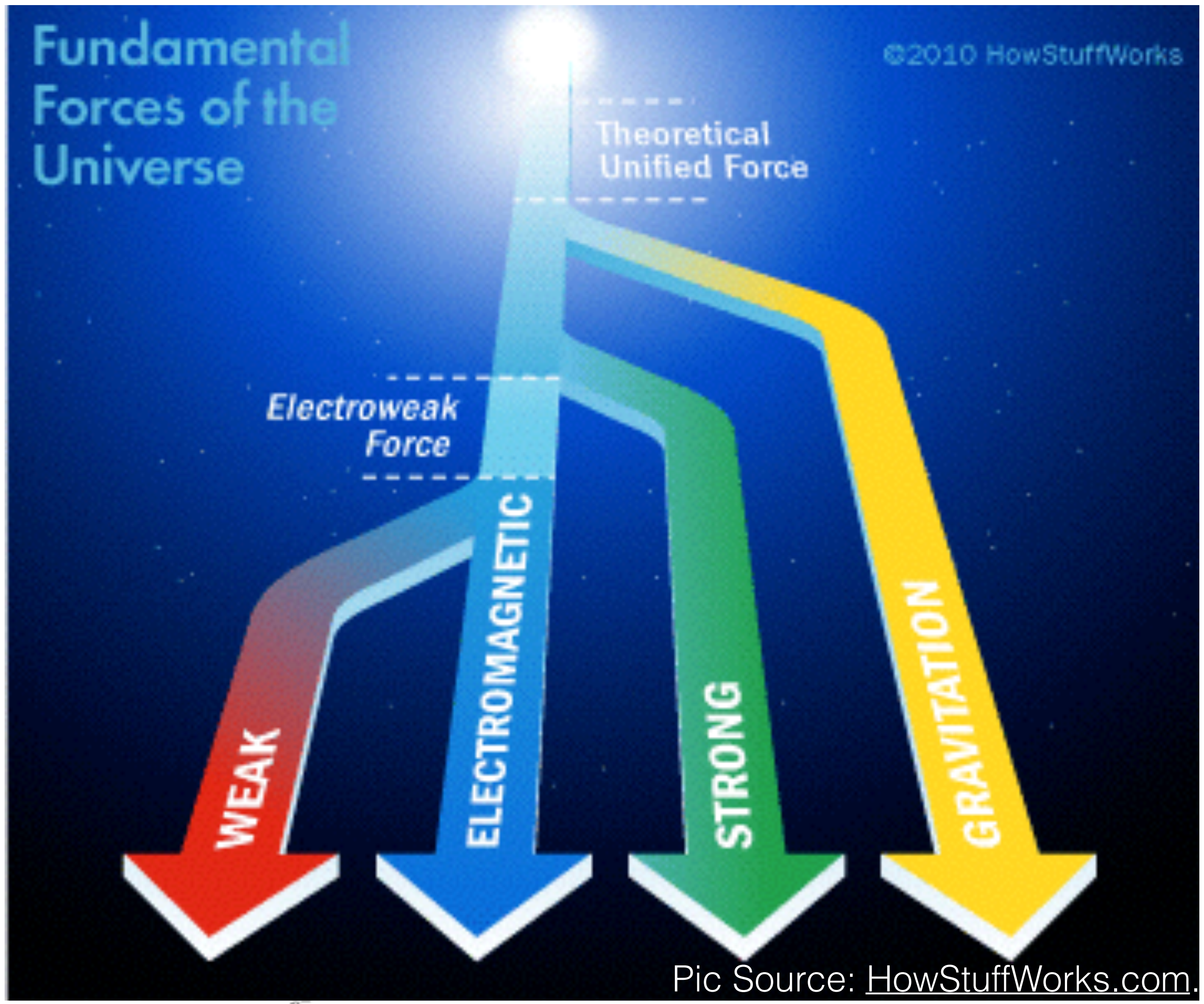


The δ_{CP} term in neutrino mixing measures **CP violation** in neutrino interactions.



We can **compare** these rates to help determine **δ_{CP}** for light neutrinos

Theories that seek to explain unification often predict certain neutrino oscillation regimes



Pic Source: HowStuffWorks.com.

Determining **which regimes describe our reality** can narrow down **which theories are valid**

δ_{CP} sign(Δm_{32})

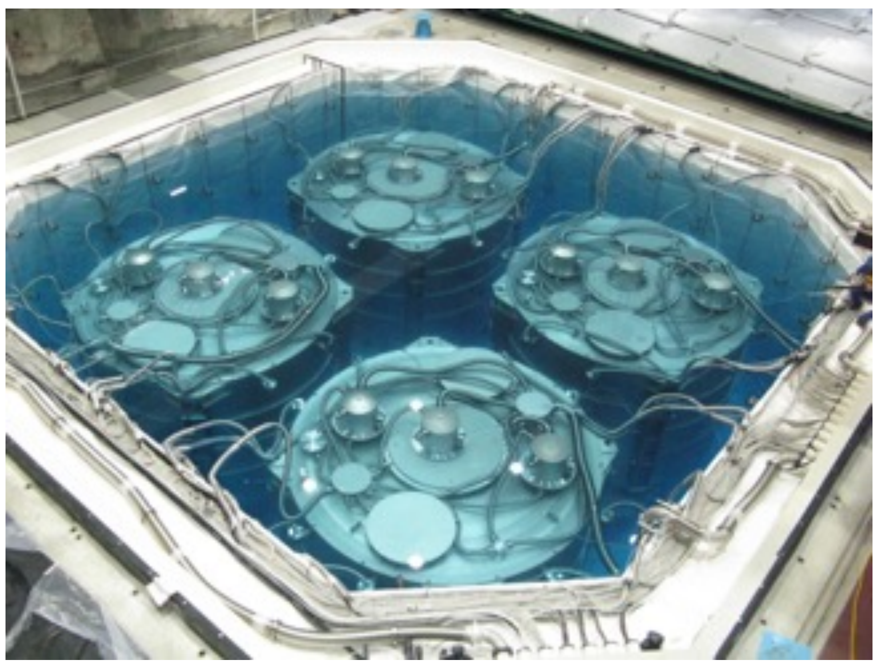
θ_{23}

PART III

Taking Action

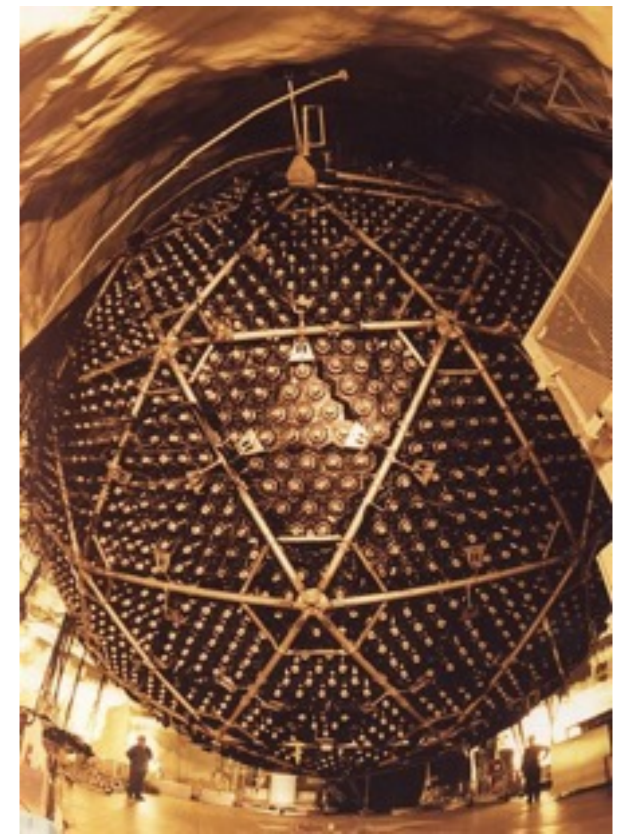
Solar and reactor neutrino experiments have made groundbreaking progress

Reactor experiments study anti- electron neutrinos produced by nuclear reactors to obtain high precision measurements of $\boldsymbol{\theta_{13}}$



Days Bay Image Source: LBL News Center

SNO detector Image Source: Wikipedia

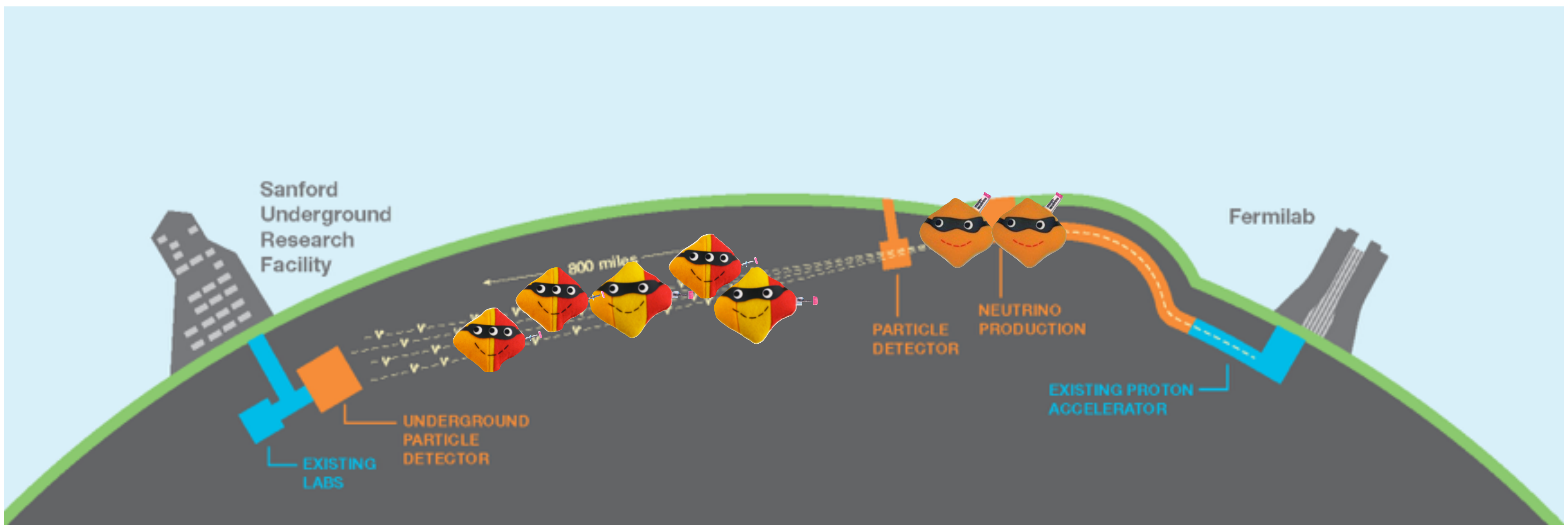


Solar neutrino experiments observe electron neutrinos from the sun to get high-precision values of $\boldsymbol{\Delta m_{12}}$ and $\boldsymbol{\theta_{12}}$

These types of experiments have also made measurements of other neutrino oscillation properties!

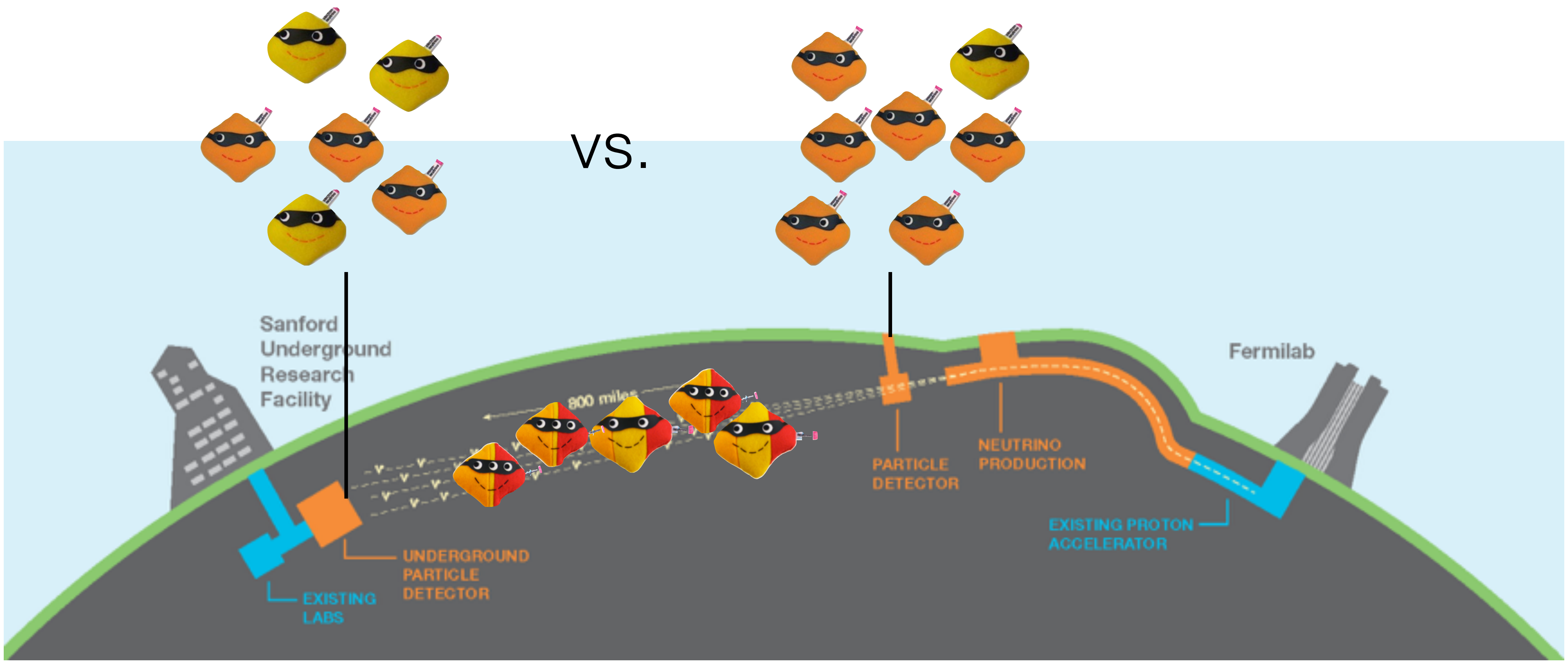
Long-baseline experiments at accelerators are aiming to finish the fight

In general, a muon neutrino beam is sent through the earth…



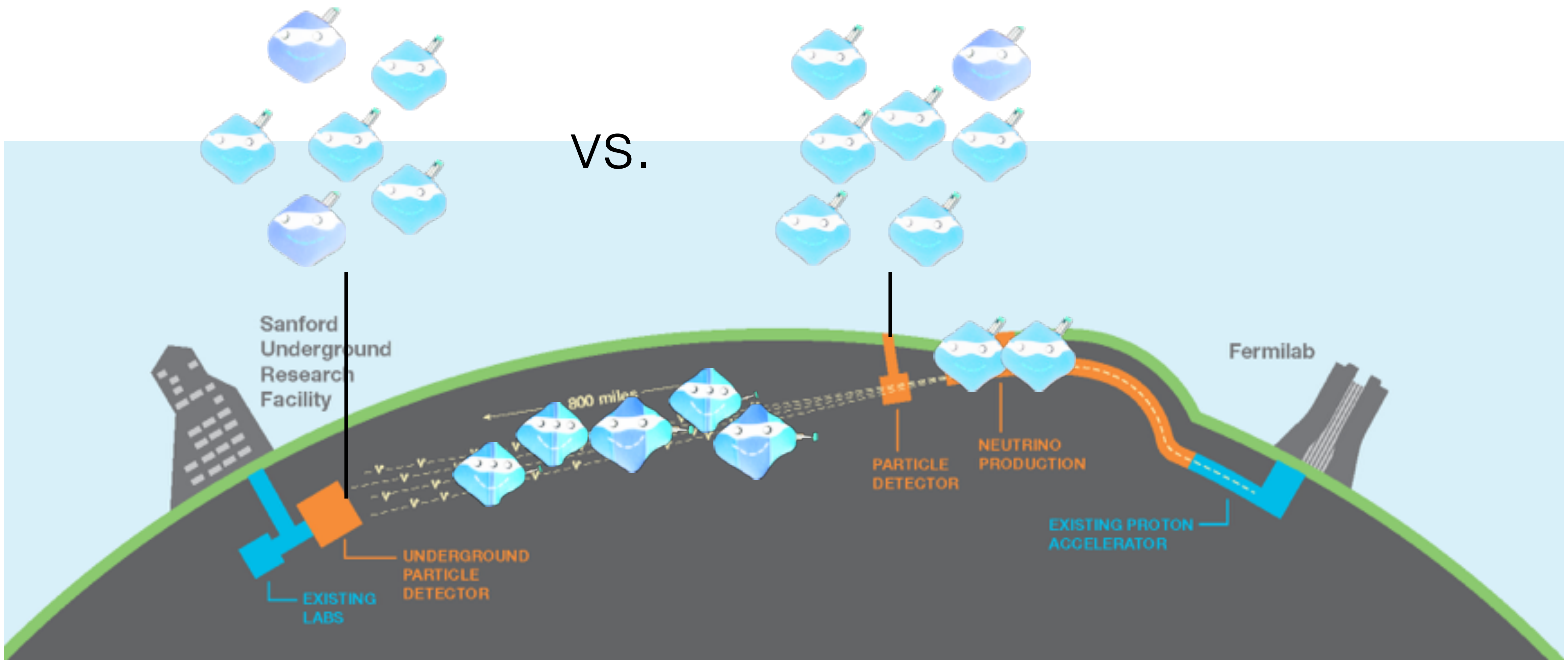
In transit, this beam becomes a mix of neutrino flavors…

At **near** and **far** detectors, fractions of observed muon and electron neutrino interactions are measured…



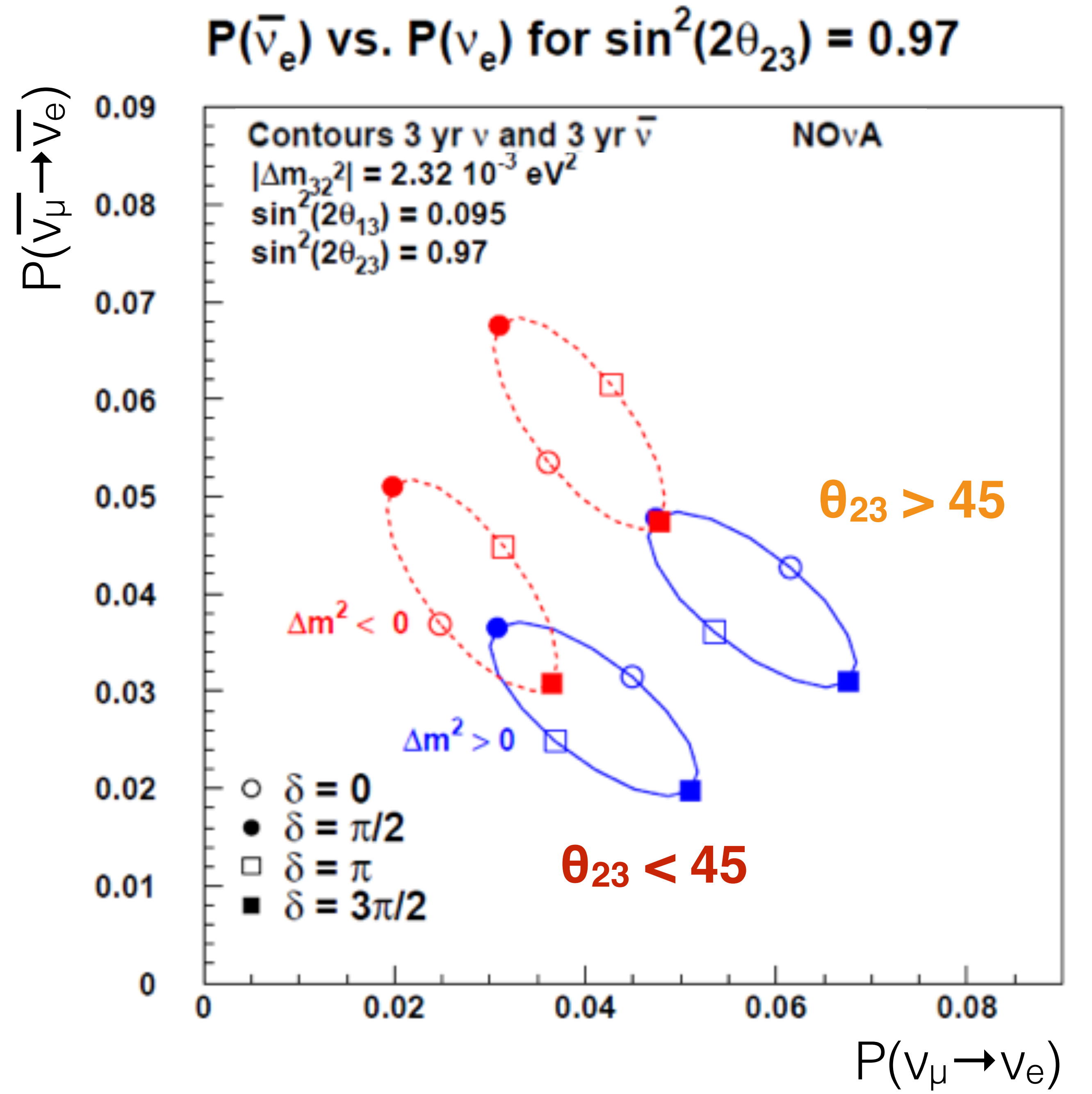
And compared to determine likely values of Δm_{32}, θ_{23}, and δ_{CP} (among others)

The same comparisons can be made for beams of antineutrinos



And compared to provide even further restrictions on these Δm_{32}, θ_{23}, and δ_{CP} (among others)

Long-baseline experiments have been designed to take advantage of this

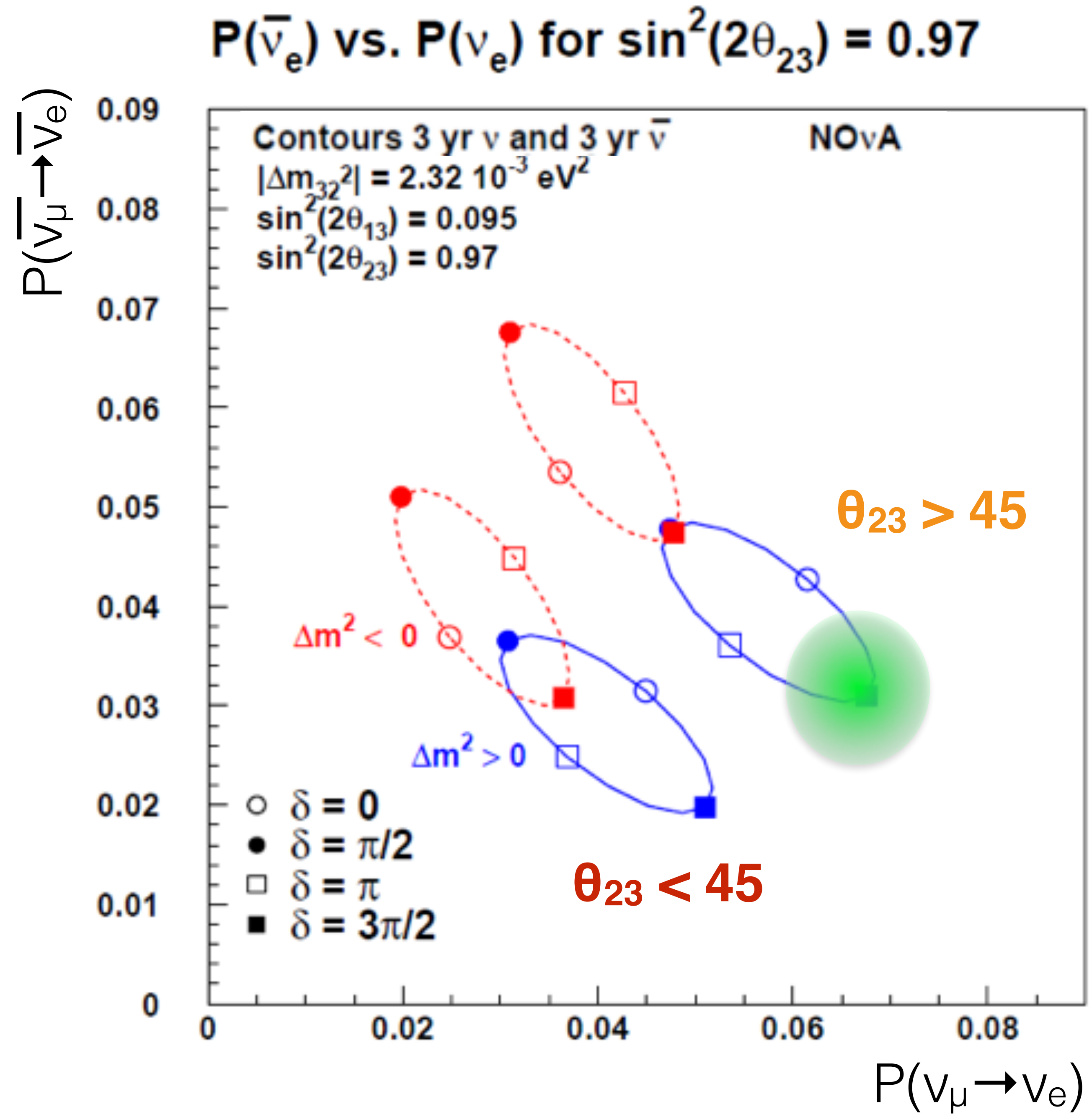


Plot Source: S. Parke, "Determining the Neutrino Mass Hierarchy"

Red and blue curves would be much closer together without the **matter effect**

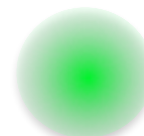
Depending on how kind nature is, a single measurement could resolve several questions at once

For the example point shown, we would be able to determine:

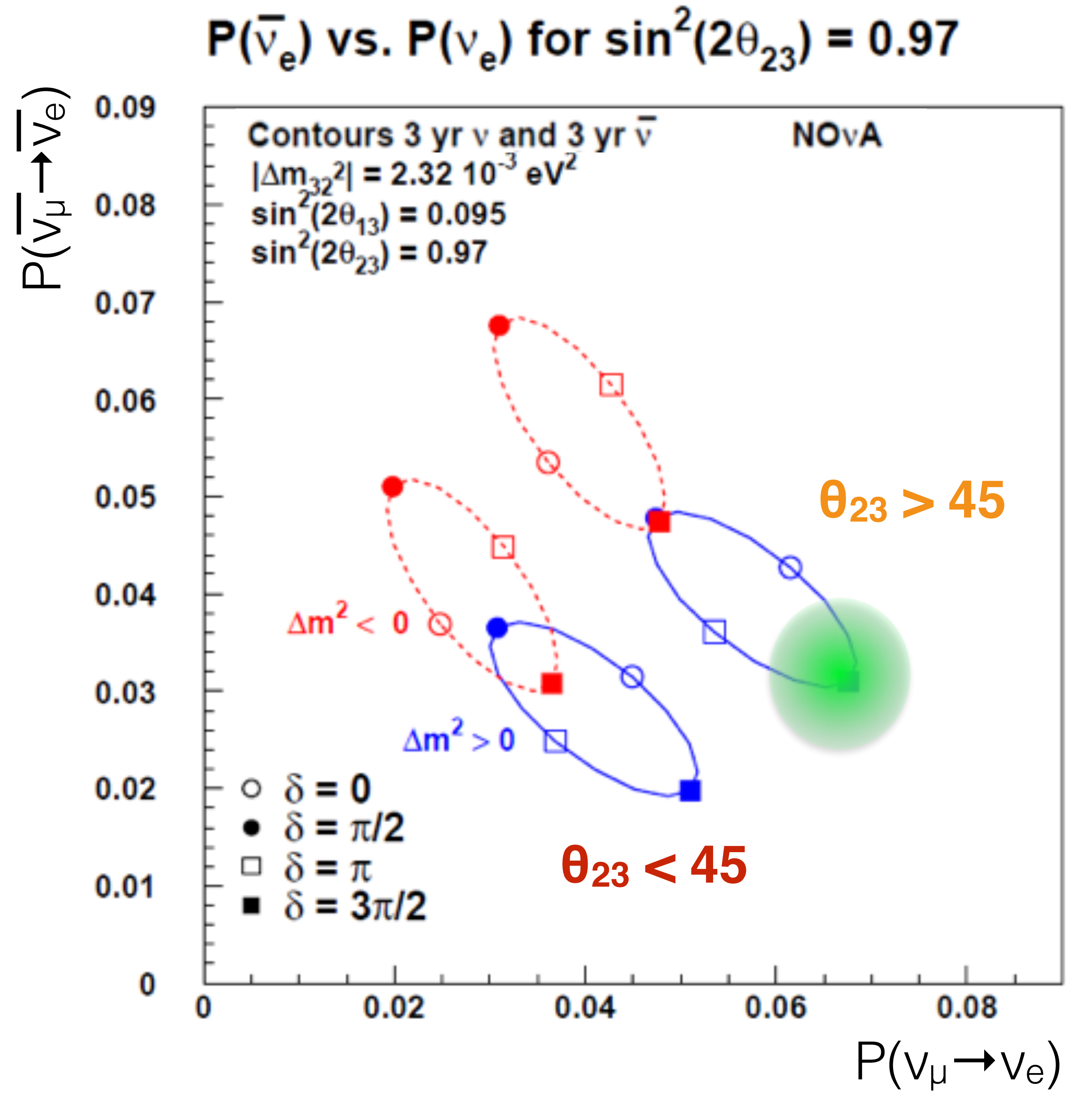


Plot Source: S. Parke, "Determining the Neutrino Mass Hierarchy"

Depending on how kind nature is, a single measurement could resolve several questions at once

For the example point  shown, we would be able to determine:

1) The mass hierarchy
2) That δ_{CP} is ~ $3\pi/2$
3) The θ_{23} quadrant



Plot Source: S. Parke, "Determining the Neutrino Mass Hierarchy"

Combining results of many different experiments will ultimately cut the knot

Image (without plushies): Fermilab Today   Image: Wikipedia, Wrestling Ring

δ_{CP}

θ_{23}

sign(Δm_{32})

Image Source

Thank you!

The End

KATRIN looks at the energy spectrum of tritium beta decays

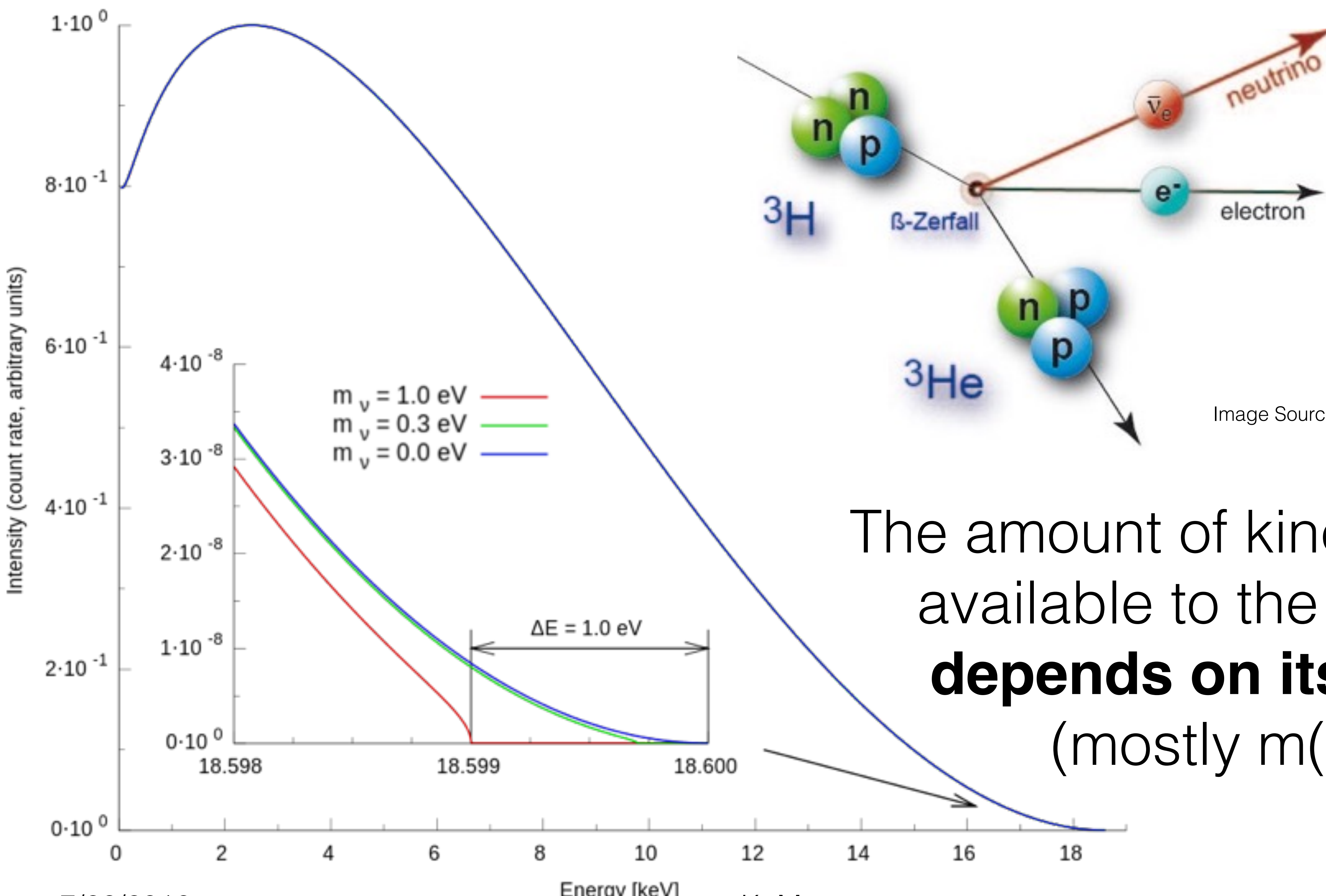
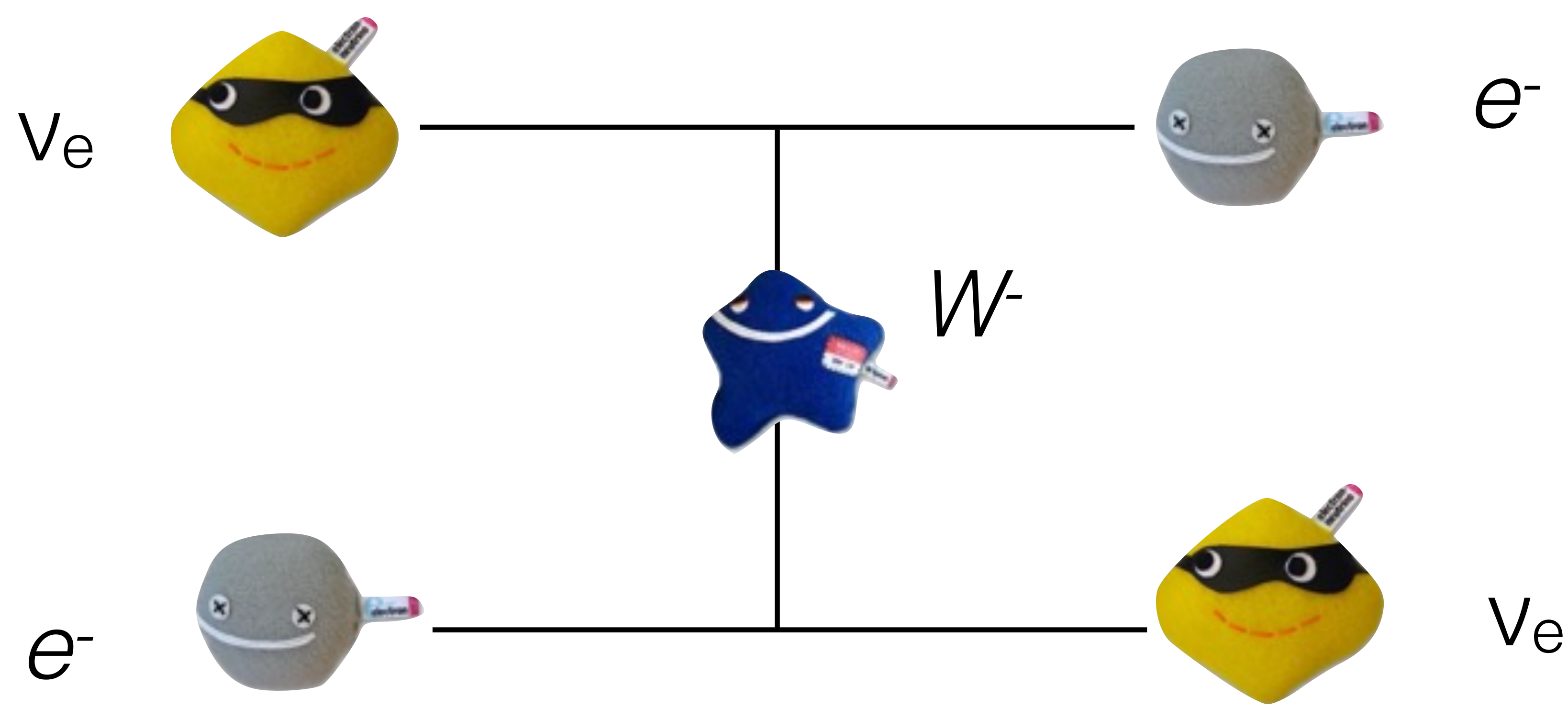


Image Source: KATRIN

The amount of kinetic energy available to the neutrino **depends on its mass**! (mostly $m(\nu_1)$)

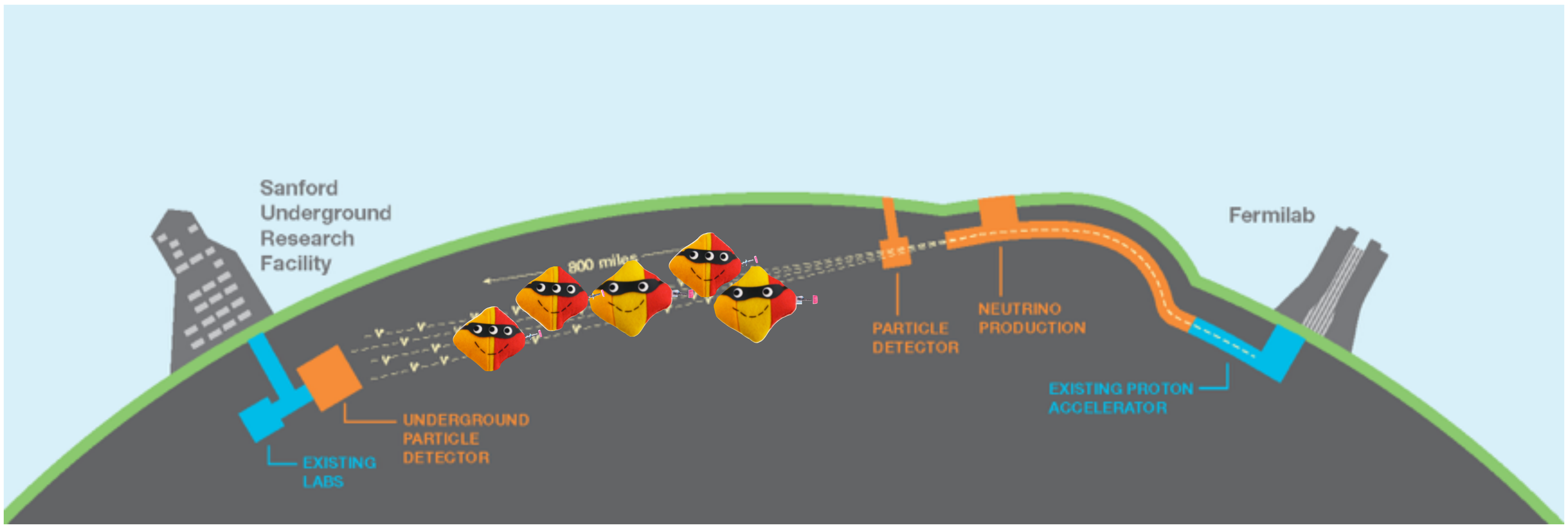
The **matter effect** amplifies the influence of the mass hierarchy

As a beam of neutrinos passes through matter, interactions with electrons "refresh" the nue component



In fact, at a high enough density, the nue component would be 'locked in', and become an effective mass eigenstate.

In a ***normal*** (***inverted***) *hierarchy:*



As a beam of neutrinos passes through **matter**, interactions with electrons **increase** (**decrease**) **the nue fraction**.

At the same time, a beam of anti-neutrinos would see the **anti-nue fraction decreased** (**increased**).